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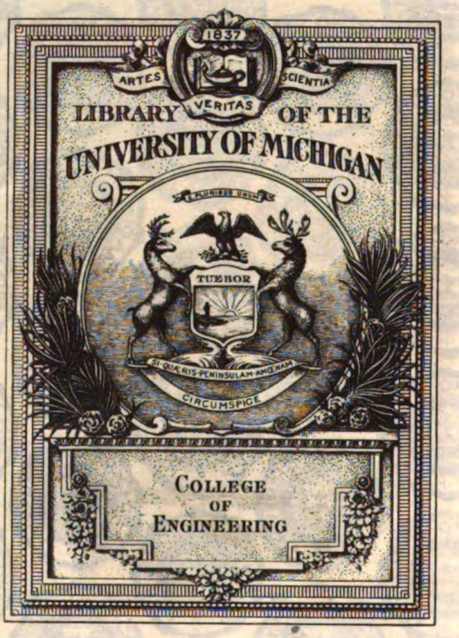


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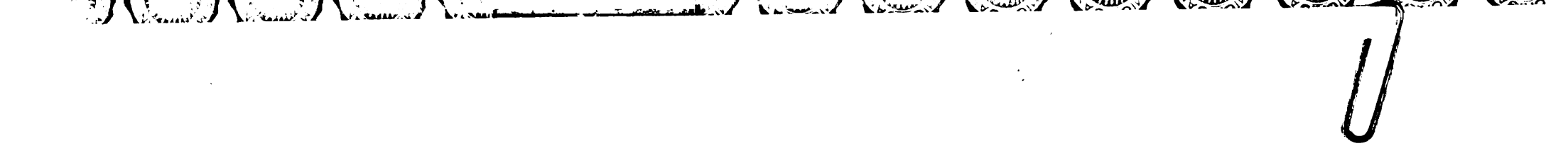

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# THE ELECTRIC JOURNAL

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# TABLE OF CONTENTS
# 1928

**JANUARY**

Present Trends of Central Station Development—E. C. Stone .... 1
Nineteen Twenty-Seven and Electrical Progress—H. W. Cope... 1
Japan from an Electrical Engineer's Viewpoint—W. L. Newmeyer .... 6
Testing Insulation with High Frequency —J. L. Rylander ..... 10
Power-Factor Rate Clauses—H. B. Dwight .. ..... 14
The Master "Mind" of the Holland Tunnel—J. P. Maxwell ..... 17
Calculation of Sags in a Transmission Line with a Broken Conductor—J. P. DenHartog .. ..... 24
The Work of Oliver Heaviside—B. A. Behrend .. ..... 26
Some Transmission Line Fundamentals —C. A. Boddie ..... 32
New 40 000 Kilowatt Turbines for the Duquesne Light Company—J. D. Schmidt .. ..... 36
An Arc-Welded Bridge..... 38
Oscillography—VIII — Auxiliary Apparatus for Staged Tests with the Multi-Element Oscillograph—Jos. W. Legg .. ..... 39
Protecting Railway Motors from Overheating .. ..... 46
The Why of the Equalizer ..... 46
The Reason for Chorded Windings—L. R. Ludwig ..... 47
Snow Removal Equipment—John S. Dean .. ..... 48
Question Box, Nos. 2785-2801..... 50

**FEBRUARY**

Alternating-Current Networks—H. Richter .. ..... 57
A Persistent Fallacy—Roger L. Knight .. ..... 58
It's the Limit—Chas. R. Riker... 58
Organization and Man Power—R. L. Wilson ..... 59
Forced Air-Blast Equipment for Oil-Immersed Transformers—L. H. Hill 60
A New Type of Turbogenerator Rotor Insulation—M. D. Ross ..... 63
Practical Considerations Affecting Quick-Response Excitation for Salient Pole Machines—P. H. Robinson.... 65
The Work of Oliver Heaviside (Concl.) —B. A. Behrend ..... 71
Fractional Pitch Winding for Induction Motors—D. F. Alexander ..... 77
Some Transmission Line Fundamentals (Concl.)—C. A. Boddie ..... 82
Unusual Vibration of a 250 000 Kw Turbine—Thomas C. Rathbone ..... 88
Electrical Insulating Oil—Dean Harvey .. ..... 96
High-Slip Versus High-Torque Motors —Their Application and Characteristics—F. J. Johns ..... 100
Oscillography—IX—Polyphase Galvanometer Control for the Multi-Element Oscillograph—Jos. W. Legg ..... 102
The Reason for the Auxiliary Commutating Winding on Booster Converters 108
Commutating Field Adjustment ..... 108
The Why of Different Temperature Ratings for Railway Motors ..... 109
Direct-Current Brush Arm Capacity... 109
Why Insulated Rivets in Transformer Cores .. ..... 109
The Transformer V Connection—C. G. Veinott .. ..... 110
Why Wavy Strips are Used as Transformer Coil Spacers .. ..... 112
Noise Reduction—John S. Dean..... 113
Question Box, Nos. 2802-2804 ..... 115

**MARCH**

How Choose a Motor—A. M. Dudley 117
Short-Hand Mathematics—Chas. R. Riker .. ..... 117
220 Kv Lightning Arresters—A New Approach to an Old Problem—A. L. Atherton .. ..... 118
Electrical Insulating Oil (Concl.)— Dean Harvey ..... 127
Recent Developments in Current-Limiting Reactors—L. H. Hill ..... 131
Characteristics of Direct-Current Motors and Generators for Diesel-Electric Ship Propulsion—C. T. Pearce .. ..... 135
An Extension of the High-Power Testing Laboratory—W. R. Woodward.. 139
Selecting the Most Desirable Type of Direct-Current Generators — Scott Hancock .. ..... 141
Graphical Flux Mapping—I—Theory and General Discussion—J. F. Calvert and A. M. Harrison..... 147
Symmetrical Components—C. F. Wagner and R. D. Evans ..... 151
A New Resistor for Use in Measurements of Impulse Voltages and Currents—Edward Beck ..... 157
A New Army Mule ..... 159
Why the Lights Wink ..... 159
Factors which Influence the Performance of a Steam Surface Condenser—U. A. Taddiken ..... 160
Stroboscopic-Neon Lamp Method for Measuring the Slip of Induction Motors—Carl C. Nelson ..... 163
Question Box, Nos. 2805-2813..... 164

**APRIL**

Changes in Design Practice—H D. James ..... 167
Oil Governors for Turbines— A. D. Hunt ..... 167
Fluid Governors for Prime Movers—I—Historical—Henry F. Schmidt ..... 168
The Relaying Problems of a Typical Large Interconnection—B. M. Jones 171
Induced Voltages in Conductors—H. B. Dwight .. ..... 173
The Grid Glow Tube Relay—D. D. Knowles .. ..... 176
Graphical Flux Mapping—II—Fields of Non-Salient Pole Synchronous Machines—J. F. Calvert and A. M. Harrison .. ..... 179
Phase-Angle Control Under Load By Means of Transformer Tap-Changing Equipment—L. H. Hill ..... 183
A High Temperature Motor ..... 186
Dielectric Losses in Oil Impregnated Paper—E. R. LeGhait ..... 187
Symmetrical Components —II—Resolution of Three Vector Products into Products of their Symmetrical Components—C. F. Wagner and R. D. Evans .. ..... 194
Recent Developments in Steam Turbine Cylinder Joint Fastenings—J. B. Walbridge .. ..... 197
Baby Synchronous Motors ..... 199
The Functions of a Relay..... 199
The Permanence of Voltage Transformer Calibration ..... 200
How to Plug Holes in Panels..... 200

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Short-Circuit Protection for Synchronous Converters . . . . . 200
Revamping Old Railway Motors with Modern Renewal Parts—John S. Dean . . . . . 201
Question Box, Nos. 2814-2825 . . . . . 204

## MAY

Electricity in the Coal Industry——E. E. Boon . . . . . 207
Recent Development in Mine Mechanization—George B. Harrington . . . . . 207
Electricity, Permissible Equipment Ilsley . . . . . 208
A Demon Enslaved—Chas. R. Riker . . . . . 208
The Electric Shovel—J. E. Borland... 209
Automatic Switching Equipment for Mining Substations—S. M. Dougherty . . . . . 214
Cost Reduction by Labor-Saving Devices—G. E. Stoltz . . . . . 217
Synchronous Motor Applications in the Mining Industry—H. Speight . . . . . 219
A Theory of Lightning—Charles LeG. Fortescue . . . . . 223
Conversion Equipment for Mining Substations—R. E. Powers . . . . . 227
Recent Developments in Permissible Type Equipment—W. D. Turnbull.. 231
Large Main Haulage Mine Locomotives—G. H. F. Holy..... 234
Trolley Wire for Mine Service—H. N. Richards . . . . . 237
Fluid Governors for Prime Movers—II—Type Characteristics—Henry F. Schmidt . . . . . 238
Organized Maintenance of Electric Locomotives for Coal Mines—John S. Dean . . . . . 243
Graphical Flux Mapping—III—Fields of Non-Salient Pole Synchronous Machines—(Cont'd)—J. F. Calvert and A. M. Harrison . . . . . 246
Overloads on Current Transformers ... 249
Now It's Radio for Locomotives..... 249
How to Clean Grease and Oil from Windings . . . . . 250
The Depth of Flutes in Transformer Cases . . . . . 250
Ventilation of Railway Motors—F. Paulsen . . . . . 251
Question Box, Nos. 2826-2829..... 253

## JUNE

Strive for Higher Standards of Public Service—H. T. Sands... 255
The Job of the Electrical Industry—P. S. Arkwright..... 256
The Intangible Interconnection between Utilities—John B. Miller 256
The Electrification of America—M. S. Sloan . . . . . 257
Politics, Propaganda and Public Service—W. Alton Jones ..... 258
Electricity—the Great Civilizer——E. M. Herr . . . . . 258
The Engineer Has a Sales Objective—C. Ernest Greenwood ... 259
We Must Keep Up With The Procession—Major H. S. Bennion 260
The Engineering National Section—E. C. Stone . . . . . 260
Power Plant Development as Seen by the Prime Movers Committee—Edwin B. Ricketts ..... 261
Should Our Water Power Resources Be Developed?—Paul A. Schoellkopf . . . . . 262
Electric Industry Faces the Task of Commercial Development—John J. O'Brien . . . . . 263
Work of the Underground Systems Committee—J. W. Sylvester .. 263
Economic and Governmental Regulation Inseparably Mixed—Edwin D. Dreyfus . . . . . 264
Heater Cord Standards—Frank Thornton, Jr. . . . . 265
Something New in Standards—W. S. Rugg . . . . . 265
The Development of Public Utility Prime Movers—A. D. Hunt.... 266
The Business of Designing Electrical Machinery—F. D. Newbury ..... 267
165 000 Kw Turbine Generator for Hell Gate—H. J. Hanzlik ..... 274
Variable-Ratio Frequency-Changer Sets C. W. Kincaid . . . . . 279
A New 30 000 Kv-a Frequency Changer 284
Vertical Transportation—A Summary of the Present Elevator Situation—H. D. James . . . . . 285
Bimetal: The Temperature Sentinel—H. E. Cobb . . . . . 288
A Theory of Lightning—II—Protection of Lines against Lightning—Chas. LeG. Fortescue . . . . . 291
A New Automatic Synchronizer—F. H. Gulliksen and H. C. Nycum..... 295
A New Portable Oil Testing Set—A. M. Wiggins . . . . . 301
Fluid Governors for Prime Movers—III—Operating Mechanism—Henry F. Schmidt . . . . . 303
Symmetrical Components—III—Calculation of Unbalanced Faults—C. F. Wagner and R. D. Evans..... 307
Portable Inverted Synchronous Converters . . . . . 311
Influence of Flux on Circuit-Breaker Top Design . . . . . 312
How to Prevent Transformer Oil Syphoning . . . . . 313
Gear Center Distances on Railway Motors—John S. Dean ..... 315
Question Box, Nos. 2830-2837..... 316

## JULY

Friendship in Engineering and Business—A. J. Standing..... 319
Progress and Success of Electrical Engineering—C. S. Proudfoot.. 320
The Value of Electrification to the Steel Mill Industry—Brent Wiley .. 321
The Electrification of No. 3 Rod Mill at the Worcester Works of American Steel & Wire Company—G. P. Wilson 323
Inductive Time Limit Control—W. G. Cook . . . . . 327
Changing from Cast Iron and Steel to Fabricated Steel—H. V. Putman and C. C. Brinton . . . . . 333
Low Voltage Cutouts For Series Street-Lighting Transformers—E. J. Haverstick . . . . . 340
The Wound-Rotor Induction Motor—Its Performance and Operation at Reduced Speeds—R. R. Sheely..... 342
A Thermal Accelerating Relay—H. E. Cobb . . . . . 345
Structural Features of an 8000 Hp Reversing Direct-Current Mill Motor—H. E. Stokes and C. P. Croco..... 348
New Subway Cars for Philadelphia.... 350
The Step Induction Regulator for Transformer Voltage Control— R. M. Field . . . . . 351
Fluid Governors for Prime Movers—IV—Operating Mechanisms (Cont'd)—Henry F. Schmidt . . . . . 354
Symmetrical Components—IV—Calculation of Faults on Systems with Lumped Constants (Cont'd)—C. F. Wagner and R. D. Evans ..... 359
Graphical Flux Mapping—IV—Non-Salient Pole Synchronous Machines (Cont'd)—J. F. Calvert and A. M. Harrison . . . . . 362
Methods of Lapping Tape—A. C. Roe.. 365
How to Refinish or Clean Switchboard Panels . . . . . 367
How to Obtain Current and Voltage in Phase from Three-Phase, Three-Wire System . . . . . 367
Two Regulators Have Same Current Capacity as Three . . . . . 367
Outdoor Trucks and Housings ..... 368
Inspection and Upkeep of Drum Type Controllers—John S. Dean ..... 368
Question Box, Nos. 2838-2844 ..... 371

## AUGUST

The Mathematics of the Amoeba—Chas. R. Riker ..... 373
The Increasing Importance of Craftmanship—W. A. Dick.... 373
Relative Frequency of Voltage Surges Induced by Charged Clouds—H. L. Wallau . . . . . 374
The Polyphase Induction Generator——D. F. Alexander . . . . . 376
Protective Grounds—V. E. Johnson... 381
Turbines for Colfax Installed..... 384
Enclosed, Fan-Cooled Motors—C. C. Nelson . . . . . 385
Contact Resistance of Electric Switching Apparatus—W. Schaelchlin .... 386
Mechanical Features for Motors and Generators for Gas-Electric Buses—C. A. Atwell . . . . . 392
Industrial Motor Applications with Especial Reference to the Rubber Industry—A. P. Regal ..... 395
Graphical Flux Mapping—V—Direct-Current Motors and Generators—J. F. Calvert and A. M. Harrison..... 399
Effects of Corona in Various Gases on Insulation and Losses—C. F. Hill... 402
High-Voltage Mercury-Arc Rectifiers—L. Smede . . . . . 403
Fluid Governors for Prime Movers—V—Governing Impellers—Henry F. Schmidt . . . . . 406
Methods of Testing Electrical Apparatus—XXV—Transformers . . . . . 410
A Four Crane Team..... 414
Fusing Instrument Transformers .... 415
Methods of Applying Relays to Circuit-Breakers . . . . . 415
The Proportionality Chart—F. Paulsen 416
Question Box, Nos. 2845-2849..... 417

## SEPTEMBER

The Lure of the Difficult—Leon R. Ludwig . . . . . 421
Economic Principles of Design—A. M. Dudley . . . . . 421
The Development of the Electric Arc Welding Process—A. R. Allard 423
Waste—Its Prevention and the Freeing of Frozen Assets—T. H. Owens.... 428
An Emergency Power Unit ..... 430
Magnetic Control for Synchronous Motors—D. E. Inman ..... 431
Automatic Vacuum Gauges—L. Smede. 437
The Development of the Feeder Voltage Regulator—E. R. Wolfert ..... 441
Protective Grounds—V. E. Johnson... 447
Fluid Governors for Prime Movers—VI—Remote Control—Henry F. Schmidt . . . . . 451
Methods of Testing Electrical Apparatus—XXVI—Transformers . . . . . 457
Largest Underground Haulage Locomotive . . . . . 462
Reactive Volt-Ampere Meters Should Be Used with Converters ..... 463
How to Disconnect Induction Regulators . . . . . 463
One Cause of Motor Current Unbalance—C. W. Kincaid ..... 463
A Spring Story . . . . . 463
Question Box, Nos. 2850-2864 ..... 465

## OCTOBER

What the A. E. R. A. Is Doing for the Industry—R. P. Stevens... 469
Some Problems of the Modern Executive—James P. Barnes .... 470

Digitized by Google

Are We Too Near The Trees to See The Forest?—Paul Shoup.. 471
We Are Not Trying To Get Higher Prices for Shop-Worn Goods——J. H. Hanna . . . . . 472
Better Transportation—Clinton E. Morgan . . . . . 472
Local Transportation Conditions in the United States—Lucius S. Storrs . . . . . 473
The Engineer in the Electric Railway Field—R. H. Dalgleish.... 474
Handling Mass Transportation—Joseph H. Alexander . . . . . 475
Opportunity in the Street Railway Industry—W. T. Rossell . . . . . 475
Analyzing the Future—G. C. Hecker . . . . . 476
Developments in Street Car Drives—G. M. Woods . . . . . 476
The Development of the W-N Drive—W. A. Brecht . . . . . 478
Speed in Street Railway Service—E. J. McIlraith . . . . . 482
Fundamentals of Blow-Out Structures—L. G. Riley . . . . . 485
Armature Coils Used to Maintain Railway Motors—A. C. Roe . . . . . 489
Operating Problems of Interconnected Power Systems—Wm. R. Hamilton.. 494
Dual-Frequency Calender Drive—S. G. Nottage . . . . . 500
Piezo-Electric Frequency Control—R. C. Hitchcock . . . . . 503
System Stability with Quick-Response Excitation and Voltage Regulators—J. H. Ashbaugh and H. C. Nycum.. 504
A Study in Black and White..... 509
Graphical Flux Mapping—VI—Direct-Current Railway Motor—Salient Pole Synchronous Machine — Universal Motor—Directional Element of a Reverse-Current Relay—Three-Pole Magnetic Contactor—J. F. Calvert and A. M. Harrison . . . . . 510
Making the Small Turbine Safe—C. L. Southmayd . . . . . 514
Methods of Testing Electrical Apparatus—XXVII—Temperature Tests . . . . . 516
How to Repair Old Squirrel-Cage Rotors . . . . . 519
Motor Drive for the World's Largest Ferries . . . . . 520
Transformer Taps Come from the Middle and Not the End of the Winding . . . . . 520
Stripping Impregnated Motor Windings—A. C. Roe . . . . . 520
A Method for Testing Transformers and Meters at Reduced Power-Factors, Using Non-Reactive Loads—C. G. Veinott . . . . . 521
Question Box, Nos. 2865-2872 . . . . . 523

**NOVEMBER**

The Public Utility Engineer—E. C. Stone . . . . . 527
Relations Between Central Station Engineers and Prime Mover Manufacturers—G. H. Cox .... 528
Selection and Application of Induction Voltage Regulators—L. G. Tubbs .. 529
Recent Developments in the Design of Impulse-Reaction Steam Turbines—R. C. Allen . . . . . 534
Methods of Selecting Electric Elevators—L. J. Kinnard . . . . . 538
Relaying the 110 000 Volt System of the Edison Electric Illuminating Company of Boston—William W. Edson . . . . . 540
The Development of a New, High-Temperature Solder—Dr. James Silberstein . . . . . 543
The New Birney Car . . . . . 546
The Centrifugal Frequency Recorder—F. S. Stickney . . . . . 547
Armature Coils Used to Maintain Railway Motors—A. C. Roe..... 549
Fundamentals of Magnetic Blowout Structures—L. G. Riley . . . . . 553
A New Type of Transformer Tap Changer—R. M. Field . . . . . 555
Oscillography—X—Sphere of Applications Expanded with New Galvanometers—Joseph W. Legg . . . . . 557
Methods of Testing Electrical Apparatus XXVIII—Insulation Tests and Tests on Single-Phase Transformers not Self Cooled . . . . . 568
A Modern Power Plant—In 1892..... 567
Cleaning Commutator Bars—A. C. Roe 568
How to Care for Circuit-Breaker Contacts . . . . . 568
How to Select Oil Circuit Breakers—F. B. Kuiskern . . . . . 569
Treated Fabric and Treated Fabric Tapes . . . . . 569
Question Box, Nos. 2873-2876 . . . . . 571

**DECEMBER**

Air Ejector Selection for Surface Condenser Installations—C. B. Tuley . . . . . 573
Standardization of Electrical Measuring Instruments—P. MacGahan . . . . . 573
Balancing in the Field—Chas. R. Riker . . . . . 574
Standard Line of Direct-Current Machines Fabricated by Arc Welding—R. S. Marthens, C. C. Brinton and F. T. Hague . . . . . 575
Operation of Direct-Current Motors in Parallel and Series with Different Types of Load—C. T. Pearce..... 581
The Development of Enclosures for Synchronous Converters—R. H. Newton . . . . . 586
Apparatus Used in the Investigation of Lightning Phenomena—Edward Beck 591
Field Balancing of Rotors—James J. Ryan . . . . . 596
Surge Voltages Produced by Direct-Current Air Circuit Interrupters—Leon R. Ludwig . . . . . 604
Methods of Testing Electrical Apparatus—XXIX—Three-Phase Transformers . . . . . 608
The Use of Steel in Switchboard Design—T. A. Kenny . . . . . 613
Ammeter Shunts for Large Capacity Circuits—Paul MacGahan . . . . . 615
Motor Field Rheostat Design—Reuben Lee . . . . . 616
Question Box, Nos. 2877-2883 . . . . . 617

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# THE ELECTRIC JOURNAL

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**Present Trends of Central Station Development**

Until a very few years ago the leaders of the power industry were concerned primarily with reducing the cost of generating electrical energy. Further improvements of this kind will undoubtedly be made, but the cost of generation has now become such a small part of the total cost of electric service that it is necessary to look elsewhere for major economies in the future. On the other hand, the tendency to build large power plants at points more and more remote from the load centers, thus involving more extensive transmission system, the insistent demands for greater and greater reliability of service, and other less important influences, are giving the unit cost of system investment an upward trend. This fact, and the vast reductions that have been made in unit fuel costs, are making the fixed charges of system investment an element of constantly increasing importance in the overall cost of electric energy delivered to the user.

More system capacity per dollar of investment must therefore be a major objective of the power system engineer. Great possibilities are to be found particularly along two lines as follows:—

Definite advance planning of system development, including proper co-ordination of adjacent systems and suitable interconnection, will result in the most effective use of the lines and apparatus installed and will bring about the lowest system cost consistent with the service standards required.

Research in system design and operation and in the operating duties required of apparatus will result both in reduction in cost of new apparatus and in more effective use of present apparatus. Recent research along the lines of field studies and tests of transient voltage and current conditions, laboratory studies of cable installation and so on, all have proved very profitable. We do not yet know nearly enough about the behavior of the apparatus we use and the performance of the systems we operate. Much more extensive research is necessary if the most reliable service is to be given at the lowest possible cost.

The electric power industry has shown a constantly decreasing cost for its service in the past. Each reduction in cost has resulted in greater use of electrical energy and consequent greater service to the public as well as greater revenue to the industry. No opportunity should be lost to further increase the use of electricity through further reductions in the cost of electric power service.

E. C. STONE.

Chairman, Engineering National Section, N. E. L. A.

**Nineteen Twenty-Seven and Electrical Progress**

Observers of our unprecedented American prosperity note one significant point—our unequalled utilization of horsepower per capita. This result is due to the marvelous development in the use of electricity, since no other form of power can be generated and applied in such an extreme variety of methods and locations. In size, for example, synchronous machines of the year vary from the 165 000 kw cross compound Hell Gate turbine generator to the synchronous motor on the gear train of a demand meter, with a rotor no bigger than a thimble. In range of habitat, electrical equipment has everywhere accompanied man, and has even taken steady jobs where no man could long survive, as for example on top of a superheated furnace in an aluminum works; submerged in water, or in explosive gas. Steam, gasoline or compressed air machines are relatively limited in their habitats.

Electricity long ago established itself as a substitute for men's muscles. It is now rapidly learning to perform the simpler functions of their brains. This does not mean, as some fiction writers attempt to portray, that men will ever serve intelligent machines, but that increasingly intelligent machines will serve man. The unskilled muscular laborer is disappearing. Perhaps he will be followed by the unskilled brain whose functions are merely perception and routine action. Of the human senses, electricity has already acquired several. Various electric machines can "see"—one built this year successfully sorts materials for color, another keeps accurate track of the density of smoke. Electrical "hearing" has for long been well-established, but this year produced new feats in accuracy of ear, such as the ability to detect the sound of an airplane above other noises, and thereby turn on landing lights; and an analyser which quickly measures the loudness of various components in a noise, and indicates the source, a powerful weapon in the struggle for silence in machinery. The Televox, an outstanding example of intelligent hearing, has been so widely described as to require only mention.

There have been electric voices, too, for years, but none which combines accuracy of tone with loudness as does the new "exponential" horn. In the sense of touch, man cannot compare with electricity. Relays perfected this year act powerfully at the touch of a dewdrop, or the mere approach of a man's hand. Devices for measuring accuracy of surface show a variation of one fifty-thousandth of an inch on a surface that may

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be moving several miles a minute, or the vibration of a standard turbine blade at full speed and full load.

In the senses of smell and taste, electricity has not gone far, but one of this year's devices can perceive instantly a variation of one percent in the mixture of two odorless gases, a feat beyond the keenest human sense.

Not among the five usually named, but entitled to rank with them, is the sense of time. In this, also, electricity excels. Laboratory methods enable the production and measurement of intervals as small as two hundred-millionths of a second by the timing of electricity's flow over a measured course. The year's new frequency meters indicate to 0.01 cycle, or one six-thousandth second, and a simple means of testing the ordinary watthour meter checks to 0.01 second. The latter two developments operate by beams of light. These contrast forcibly with circuit breakers, developed some time ago, which after opening carefully count five seconds, and reclose. If the short-circuit still exists, they open, count fifteen seconds, and try it again. Undiscouraged, should the fault still exist, they wait a minute and a quarter, again close, and then, if the short-circuit hangs on, lock themselves open.

Discretion, the exercise of judgment, is perhaps the citadel of human superiority, but devices perfected this year can distinguish a short-circuit from a legitimate load of even greater amount, decide which of several feeders in parallel is affected, and disconnect the fault—all in a few hundredths of a second.

In the power industry, bound up as its fortunes are with centralized generation, large power units are yearly mile-stones of progress. Such importance attaches to the 194 250 kv-a cross compound turbines for the Hell Gate Station, which set a high mark for 1800 r.p.m. machines. Speed, with its saving of size and weight, is the vital essence of the turbine generator. Every increase in speed is thus peculiarly interesting, as representing a new advance in special characteristics. Similarly, increases in speed are made this year in big synchronous condensers—10 000 kv-a machines of 900 r.p.m., instead of 720 r.p.m., as heretofore and 30 000 kv-a machines of 720 r.p.m. instead of 600 r.p.m. Such increases in speed also raise the ultimate limit in size, a matter of interest in turbine alternators, whose rapid growth shows no slackening. At present this limit, (apparently the weight of rotor the railroads can handle) is not very close—275 000 lb. capacity cars are available, and the Hell Gate rotor weighs but 158 500 lb. The maximum capacity of units is also expected to be increased by operation in hydrogen gas, a large machine of this sort being now under construction.

It is, of course, desirable that machinery should be shipped complete from the factory, rather than assembled at destination. Formerly 15 625 kv-a was the largest turbogenerator that could be shipped complete. Changes in design, including skeleton structural steel frames, now permit complete shipment of 100 000 kv-a units.

The biggest waterwheel generators (for Conowingo) 38 feet in diameter are interesting both for their high speed excitation, and in comparison with even bigger machines built two decades ago for the New York Subway. Still the world's largest, physically, the old machines show only a fraction of the capacity per pound of active material of the new—a result of the use of better iron, and other materials, and better ventilation.

A 40 000 kv-a frequency changer, a 21 000 kv-a single-phase generator, as part of a frequency changer, and a railway converter to carry 6000 kw for two hours, are other record-breaking synchronous machines. Then there is a 28 000 hp induction motor, part of a variable ratio frequency set. Increasingly large induction motors for general use are not to be expected, the trend being toward synchronous motors in the larger capacities.

Two groups of tremendously large circuit breakers were built in 1927, each of two and a half million kv-a rupturing capacity; one, an outdoor type for 220 000 volts, the other, indoor for 15 000 volts. The mechanical forces in circuit breakers increase very rapidly with increase of current. The latter circuit breaker was necessarily built to cope with terrific stresses.

Aside from equipment of record-breaking size, are many machines more interesting for other reasons. Big frequency changers are proof of the persistence of 25-cycle zones; often hemmed in by 60 cycles but increasing in load as they decrease in area. Beside the 40 000 kw machine there are 25 000 kv-a variable-ratio frequency changers, which can be set to transfer a fixed amount of power regardless of conditions, and a 30 000 kw machine destined for a city of less than 30 000 population, in a mining district. Lack of space in New York City produced synchronous converters dwarfed in dimension but huge in output, 4200 kw, 25 cycles, for lighting. Double direct-current brushholders, cast aluminum supports for alternating-current brushes, and die-cast bronze brushholders, are notable features.

In connection with the Conowingo power project are the largest single-phase transformers; seven self-cooled monsters of 33 333 kv-a each now, 50 000 kv-a eventually, when air blast is applied to their radiators.

Efficiencies, already high, have crept steadily nearer the unattainable goal of 100 percent, which is, however, but a fraction of a percent away.

Many huge transformers include tap-changing in some form, depending on conditions—a result of the tying together of high-voltage systems, in which voltage regulation by generator field rheostat is not practicable. The number of users of Inertaire, which prevents sludging of oil, have doubled this year. Transformers as large as 25 000 kv-a have been built with an air blast against their radiators, to increase their rating. Reactors, simple in principle, have been further developed, being increasingly needed to meet increasing

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concentrations of power. Concrete core, exposed reactors have been given heat-proof insulation; very large reactors, 1029 kv-a, are immersed in tanks of oil.

The old direct-current three-wire underground network has survived in congested city areas due to its superiority from a service standpoint, but has introduced the handicaps of great expense, congestion of cables and substations, and the complications incident to converting equipment. The alternating-current four-wire low-voltage network avoids these difficulties while preserving a high standard of service. Its progress this year bears the promise of its coming importance. Transformers feeding such networks, mostly underground, usually have high impedance, include some form of grounding and disconnecting switch, and sometimes a tap changer. The sizes range up to 500 kv-a three-phase. Connecting the transformer to the network is an automatic network protector, a steel enclosed low-voltage circuit breaker controlled by intelligent relays. It not only protects the network against faults in feeder cables and transformers, but also allows connecting or disconnecting the transformer from the station. Though rugged, it is so sensitive as to act on reversal of the transformer exciting current.

The switchboard has seen many changes since it started its career as a wooden structure carrying knife switches. It has been of marble and slate, and now turns into steel. Instead of a mere panel near the wall, it has developed into cabinets and trucks on rollers, that can be pulled out into the room, with all their equipment; or perhaps into swinging door-like panels, whose backs can be examined from the front, so as to be set close to a wall. Then there are boards shipped completely built and tested from the factory, in operation perhaps a day or so after arrival. Probably the smallest steel-clad switchgear is that which controls the ventilating fans supplying the breath of life in the Holland vehicular tunnel. Other truck-type panels, the largest, weigh 6500 lb., but can nevertheless be readily handled by one man. Steel-cabinet boards have been used at 12 000 volts outdoors in Chicago, the phases being segregated, 50 feet apart. High power direct-current circuit breakers have finally followed the example of alternating-current circuit breakers, leaving the switchboard completely, in a recent important street railway plant. Mounted separately, protected by disconnects and remotely operated, greater safety and less maintenance is expected.

Engineering progress often abandons one path, and some years later under more favorable conditions returns to it again. So the short-wave radio, discarded decades ago, has now returned to most important duties. The mercury-arc rectifier, developed before the War to 2000 ampere ratings, and the operation of a car with direct-current motors from an 11 000 volt alternating-current trolley—was for some years put aside. Now it is again important—new 1250 ampere 600 volt steel-tank rectifiers maintain their vacuum without attention, and the puzzle of a suitable seal has been solved by soldering to a metalized surface on the porcelain bushings.

The street car is another example of rebirth. Thirty-six years ago, the abandonment of the double-reduction gear was an achievement—gears were noisy, inefficient, short-lived. Even a single reduction was thought a necessary evil. In the generation since, high efficiency, silence, and long-life have worked down from the Melville-McAlphine-Westinghouse gear for marine drive into industrial machinery and millions of silent automobiles. A modern double-reduction gear set, on roller bearings, and in a bath of oil, is much preferable to the accustomed single reduction pair, ill-lubricated, in a split case, with alignment certain to vary with wear. In connection with the high gear ratio come smaller, lighter motors, all springborne; the practicability of much more power per ton of car weight; and a silent, smooth, swift street car, able to compete with the automobile.

Approaching the goal of speed from another angle, are the six-motored articulated cars in Cleveland which, with revised stopping points, have made schedule speeds during tests in city streets equal to local trains in subways. Since most cities cannot afford subways, increased speed on surface lines is their best hope of rapid transit. Articulated cars, not entirely new, have hitherto had but four motors.

Steam railroads are not electrified every year, but this year saw more engines for the New Haven, (making 133 on that one road), new engines for the Great Northern, and for the Paulista (Brazil).

The Diesel oil engine, for a long time theoretically interesting to railways, has become practical through the development of a powerful, rugged, light-weight design. Rating 300 hp this engine weighs but 6900 lbs.—about a third of previous corresponding weights. Its record in actual services on cars this last year has been very creditable, and a 600 hp locomotive has been built weighing but 80 tons. Diesel-electric cars and locomotives will probably cover a large field of railway operation where electrification from a central power supply is not yet justified.

Electric drive of ships has been used in connection with both steam and Diesel prime-movers. Among notable electric-driven ships are several large submarines, a group of 3000 hp turbine-electric Coast Guard vessels (practically gunboats) much larger than the one Diesel-electric cutter previously built; several groups of Diesel-electric and steam-electric ferries in San Francisco Bay, and a big deep-water tanker of 3200 hp, the largest Diesel-electric equipment actually built, though even larger vessels will be reported next year, being already announced. It is interesting that electric drive, adopted in the past on grounds of luxury, or of military superiority, is making its way in strictly commercial shipping where it must justify itself under rigid scrutiny of costs.

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There are no electric-driven airplanes, but many products of the electric manufacturer have helped in the phenomenal flights of 1927. Every American plane distinguished this year in overseas flights has had micarta control pulleys. Micarta propellers were used on the first successful Hawaiian flight and by the second successful Dole contest flyer to Hawaii. They are likewise on the Secretary of War's official plane. On Byrd's flight, his radio was supplied by a wind generator with micarta propeller.

A most important aid to aviation is the night illumination of air lanes and airports. As the night mail hums through the dark sky, its patch is marked by a succession of upward waving fingers of light. These beacons dotted across the country are fed by farm-lighting sets. To provide against possible failure of such sets, an automatically-starting twin set has been developed, which immediately goes into action should the first one falter. Automatic-starting farm lighter sets are also widely used for emergency power supply in public halls and assembly rooms, where some states require them. The reliability of such little isolated generating sets is also shown by their adoption this year as current supply for telephone systems.

Airport flood-lighting did not originate in 1927, but the automatic turning on of these lights by the sound of the plane was first accomplished this summer. This is merely a typical case. The same sound-sensitive relay can be arranged to respond to any specific steady noise. It discriminates both against dissimilar noises, and similar noises of casual or intermittent character.

Experiments with 10 000 watt Mazda lamps indicate that such units have a distinct field of usefulness, which may in some cases encroach on the limited field still held by the arc. Further progress has been made in lamp manufacture, tending both to greater speed and better quality. A striking example of light applied to enhance a natural wonder was the illumination of the Natural Bridge of Virginia. The great Holland vehicular tunnel under the Hudson, interesting in so many ways, is likewise an illuminating achievement, both for its elaborate signal system as well as the regular lighting.

Much progress has been made in street lighting. The unequalled system in St. Louis was first lighted. Hollowspun concrete poles have been further developed, and ornamental fittings of great size and high power have appeared. A new low-voltage film device short-circuits a defective lamp, and prevents radio "static" sometimes caused by lamp outages. Aluminum has become important in the illuminating field, as in so many others. Not only massive ornamental lighting heads, but the whole system of floodlights has gone over to the light metal. Outdoor lighting has also put the selenium cell and the mercury switch to successful practical use. Indoor lighting experts have developed new fixtuers too many to mention.

The speed of electric power in the various industries is so rapid that but a few chance-chosen points can be touched. The most modern, most completely electrified steel mill in the world was opened. Probably the most conspicuous of the many achievements there was the great 52 inch mill, whose rolls automatically adjust themselves after each operation, so that a single man controls the entire operation—and turns out more accurate steel. The main motor room contains 54 600 hp in eleven units. Other steel industry items include a 3000 hp motor of new design, for a reversing mill; a 2500 hp motor which varies but one r.p.m. from no load to 100 percent overload, and the heaviest powered tandem strip mill.

A new, odd frequency has appeared at each end of the scale, for special purposes. For turning over paper machinery very slowly, a frequency converter supplies from four to six cycles. At the other extreme are the special power circuits for portable tools, at 180 cycles. Where many such tools are used, the special circuit is warranted in order to use 10 000 to 20 000 r.p.m. three-phase induction motors in the tools instead of the customary universal motors, which are more expensive to keep in order.

The lumber industry has applied electricity to the particularly difficult log carriage drive, finding the special requirements exactly met, curiously enough, by an elevator motor. Another extremely difficult drive electrified in 1927 was a Pacific Coast band saw, driven by a direct-drive, ceiling-mounted, 350 hp synchronous motor.

In all the exciting adventures of the oil industry this year, electricity has been a faithful partner. The drilling of wells through almost impossible strata has been met by the Hild drive, even though 700 pounds per square inch had to be put on the mud forced down the well. In Texas, where cities sprang up in a few months, power plants of many thousand kilowatts sprang up as rapidly. In the more stable part of the industry, represented by pipe lines, steam and oil engines were supplanted by electric drive under a sudden need for 40 percent increased capacity. Delivery was quicker, the cost one-tenth, the attendance one-half that of steam. Such results make the entire field of pipe line pumping a fair prospect for electric power. These pipe lines, stretching from Wyoming and the Gulf to the Atlantic, and dotted with pumping stations, form a transportation system comparable to the railroads, though quite unknown to the average man.

In the textile industry, electricity has meant more uniform quality and faster production. The demand of every woman for silk, which has left the silkworm's capacity far behind, is met by tens of thousands of little motors spinning at 6000 r.p.m., each with its cup in which rayon artificial silk thread builds up. Worsted, cotton and silk yarns are produced better and 10 to 15 percent faster by a special revolving rheostat, which maintains a constant tension. A new quick-change grooved-pulley drive produces better cotton, allowing a very quick change when the size of yarn is

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altered. Machines which knit silk stockings can be run faster because a new electric control slows them down when stitches are to be dropped.

It is interesting to see how the demands of various industries have brought forth motors especially adapted in character, sometimes even contrary to what was formerly regarded as their inherent nature. A few years ago, only very small motors could safely be connected directly across the line in starting; and synchronous motors were for decades supposed scarcely able to start themselves, let alone a load. But industry wants big motors of hundreds of horsepower to start across the line, for simplicity; and it wants to use synchronous motors, for good power-factor. And it gets both these things. New synchronous motors, direct coupled to heavy loads, start directly on the line; and seem to thrive.

In coal mines where explosive gases lurk, a locomotive with new 40 hp explosion-proof motors travels safely in gaseous sections, getting power from a cable reel instead of a trolley.

For operation in grit, dust, water or corrosive fumes, motors have long been totally enclosed. The severe reduction of capacity due to lack of ventilation has been accepted not cheerfully, but philosophically. A new motor for such places ventilates itself through a long duct. With all openings closed, it rates 30 hp. Opening the ducts makes it rate 250 hp. Putting a blower on the end of the duct raises it to 300 hp—270 hp, one might say, taken out of the air.

Industrial control, the brains of electric drive, assumes so many new forms that only a few can be mentioned, but among them are applications of thermal control based on bimetal devices, developed to unprecedented reliability. One such device is self-closing after opening on overload, thus saving a machine operator a trip to the starter. Line starters for squirrel-cage motors have thermal relays and may be oil immersed. These two are chosen at random from many developments aimed at giving the electric drive a brain.

Static condensers, formerly regarded as laboratory devices, have become practical, reliable and often extremely profitable. Built in quantity production, they are installed where the cost of poor power-factor is appreciated. One typical equipment in a factory is saving 93 percent of its cost annually, in power bill reduction. Beside such large condensers, which seem sure to become more prevalent, small units are available for individual motors, where cost has hitherto been prohibitive.

Small motors, like electric lamps, touch the average individual more closely than other devices. Because of their enormous number and the lack of attention they receive, detailed study of their design and performance, in specially-equipped laboratories, is warranted. Among the many new forms, called forth by special requirements, is a motor for electric refrigerators or oil burners which is extremely quiet—a valuable asset in competing with a cake of ice or when attached to the sounding board formed by a furnace and heating system.

Electric heat, so long regarded as expensive, makes progress as people realize that cost is not to be figured only in cents per kilowatt-hour but in the total cost of acceptable finished articles. Uniform, exact heat treatment has made various electric furnaces installed this year exceedingly cheap, for factories which make ball bearing races, small tools, and machine parts, automobile parts, brass tubing and the like. Furnaces with rotating hearths pass the articles through a precisely correct heat cycle, and automatically dump them to the quench. With others, parallel streams of different parts are fed through various cycles simultaneously. The world's largest all-electric furnace went in service this year, and is showing extraordinary savings, principally in less labor, less spoilage, greater output. Other electric heaters keep railroad track switches clear of snow; or provide comfort, hot wash water, a drying rack, and a lunch-warming shelf for the outside laborer.

Electric welding is widening its application rapidly. The first all electric-welded railroad bridges were built in 1927; many old bridges were so reinforced; it has replaced other processes in making transformer cases, in steel truck switchboards, in bedplates for machinery, perhaps most striking of all, in entire lines of rotating machines. Synchronous motors and generators for example, are now built without a single casting in stator, rotor or bedplate. It is possible, without any machining of the stator to produce an even more accurate and rigid structure than formerly. Turbine generators and synchronous condensers have fabricated frames. It seems probable that except for small complicated parts castings will have almost completely disappeared from most electric power machinery in a few years. So important a new development has merited, and received, a new portable welding set, designed and built as an iron-clad portable unit, instead of being, like most sets hitherto, an assembly of stationary-type machines on a cart.

Research, the development of instruments, the study of materials and processes, the continued study of lightning phenomena and the characteristics of transmission lines, unfortunately cannot for very lack of space be here discussed. Such omission is not a reflection upon their importance. Such fundamental things are like building-foundations under ground, the unseen bases upon which the towering achievements of another year will be erected.

H. W. Cope.

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# Japan from an Electrical Engineer's Viewpoint

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Japan being a far off country, the ideas of the average American concerning it are apt to be rather vague. Much has been written by popular writers concerning social, political and living conditions, but information concerning engineering and construction development in the electrical field is yet confined to only a limited number of articles, many of which predate the earthquake of September 1923. The purpose of this article is to give a picture of some of the development since that time, and also to give an idea of the actual conditions in the field from the view point of an electrical engineer.

THE mention of Japan instantly brings to mind the earthquake disaster. It is commonly supposed by those who have not visited the country that Japan is a place where such catastrophes are to be expected frequently. However, this is not the attitude of mind there. While the people know that such things may happen, they really do not expect a reoccurrence of much severity. Within less than a year of the disaster the people were sufficiently recovered to work definitely for the future, and since that time construction has been going on at a swift pace.

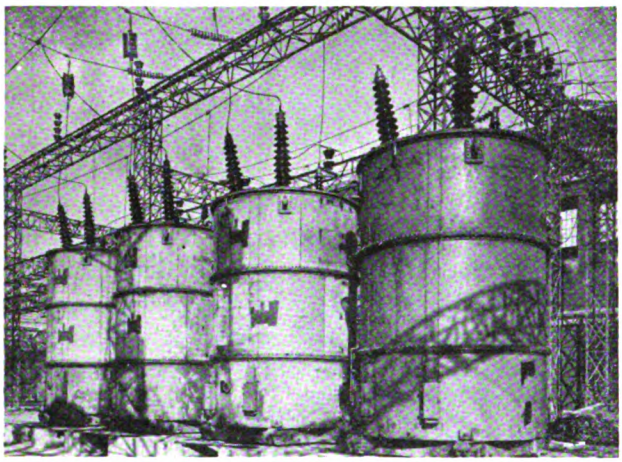

FIG. 1—A MODERN JAPANESE, TRANSFORMER INSTALLATION
Each transformer is rated at 25 000 kv-a, 11 kv delta to 140 kv, star connected, and is provided with taps for 66 kv star connected. The transformer cores and coils were shipped separately and were assembled in Japan.

At the time of the earthquake, Yokohama the seaport, twenty miles from Tokyo, was near the center of the disturbance and was much more damaged than Tokyo. While badly shaken, Tokyo escaped with severe damage to a relatively few buildings, and the wiping out of very large sections of the city by fire. One section known as the Marunouchi district contained a large number of brick buildings which escaped almost completely uninjured. It would almost seem as though the earthquake had nodes, where the disturbance was not great enough to cause much damage. For example, the Tokyo Railway Station building, a large brick building with several domed roofs, escaped with no damage, as well as other numerous brick buildings, while a nearby building recently built was very badly damaged. This may however, have been due to the type of foundation, etc. used.

The earthquake determined future general construction in that it caused the use of heavier reinforcement and monolithic type construction. Most foundations and building frames are now built so tied together that in the event of a heavy shock the structure will rock as one piece, rather than shake itself to pieces. The elevated railway structure had previously been of earth and masonry. Many of the new extensions are now in the form of a heavy reinforced concrete structure with cross tie members. This incidentally gives a very solid roadbed. One of the pleasing things about the Tokyo elevated is the smoothness and quietness of operation of the trains. Such absence of swaying and rattle would be a pleasing change to a New Yorker or Chicagoan.

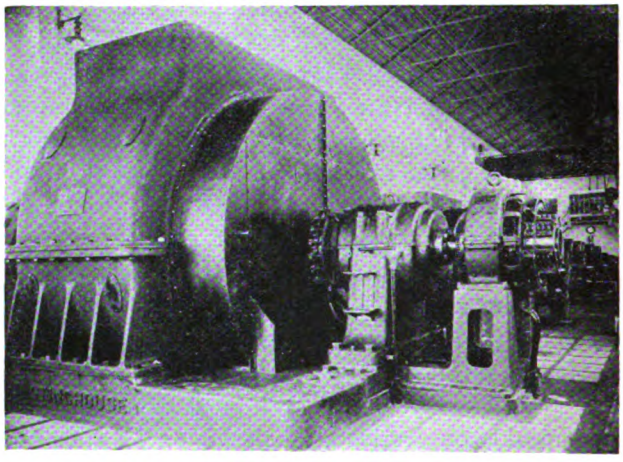

FIG. 2—A 120 000 KV-A SYNCHRONOUS CONDENSER SUBSTATION OF THE DAIDO ELECTRIC POWER CO.
The machine in the foreground is a 30 000 kv-a condenser.

The government railways operate not only the main railway lines in the country, but also operate the elevated in Tokyo and the interurban system between Tokyo and Yokohama. The electrification work is divided into two main parts; the first being the electrification of the main railway line, the second the development of the Tokyo elevated and Tokyo-Yokohama interurban system. At the present time the elevated is being operated at 1200 volts but all substations built recently are arranged to be changed over to 1500 volts,

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probably this year. The interurban line and the main line is already operating at 1500 volts. The elevated trains usually consist of four to seven cars, two or three of the cars being motor cars. Each motor car has four 150 hp motors.

The main line leaving Tokyo for the south-west is now electrified for a distance of approximately 50 miles. All passenger trains are now pulled by electric locomotives, though the freight trains still have steam locomotives. However, as the freight train terminal is on the outskirts of the city, only electric trains run into the main station.

Most of the substations are new and the few remaining old substations are being replaced by more modern ones. The substation buildings are reinforced concrete but are much lighter than one might expect in a place where severe earthquakes may occur. The

FIG. 3—THE MODERN, REINFORCED-CONCRETE ELEVATED STRUCTURE OF THE JAPANESE GOVERNMENT RAILWAYS IN TOKYO

most recent substations are exceptionally large for railway substations. The main ones range from 8000 to 12 000 kw. The substation converting equipment consists chiefly of synchronous converters. Two 1000 kw 750 volt machines connected in series forming a 2000 kw 1500 volt unit is the standard unit used. For service between Tokyo and Yokohama and for elevated service around Tokyo, there is at present more than 75 000 kw in substation capacity. Excellent results have been obtained with the modern high-reluctance commutating-pole machine on 1500 volt service. The converters are further protected by direct-current high-speed circuit-breakers. Flashovers of machines even on feeder short-circuits have been practically eliminated.

Some of even the largest substations are arranged for automatic operation and have been giving very satisfactory service. The automatic control has proven reliable. For ease in handling, and particularly at times of trouble the automatic features have proven of considerable value. Further installations are being made.

The first thing that occurred to the writer when he visited the substations on his arrival in Japan (about one year after the earthquake) was to see what special precaution were thought necessary to guard against future "shakes". Contrary to expectation it was found that little or no more precaution was taken than in America. The switchboards are a little more heavily braced and high-transformers are sometimes specially braced as well as being bolted to their foundations. However, the synchronous converters do not have their foundations bolted, being simply grouted to the base. There have been a few minor earthquakes since these stations have been in operation but they have never been damaged, nor has the service been interrupted.

## HYDRO-ELECTRIC POWER PREDOMINATES

Japan is a country of mountains with many swift rivers. It is therefore only natural that a great deal of the power development has been hydraulic rather than steam. This in turn has led to the use of many high-voltage transmission lines, as the power sites are some-

FIG. 4—AN ELECTRIFIED TRAIN OF THE JAPANESE GOVERNMENT RAILWAYS

This seven car, multiple-unit train is in interurban service between Tokyo and Yokohama.

times distant from the large cities. The voltages used for transmission of any great distance are usually 66, 110, or 154 kv. All new lines of any great length are now built for 154 kv operation. The transmission systems are quite long in some cases, going up to as much as 200 miles. These long distance transmission lines in turn require the use of large condenser substations at the receiving end, and some of the largest power substations in the world are in Japan. Furukawabashi Substation (which is at Osaka, the Pittsburgh of Japan) of Daido Denrioku K.K. today has 120 000 kv-a in synchronous capacity. The most recent addition is a 30 000 kv-a condenser.

It is very interesting to note the construction facilities and methods in general use. The installation of such large equipment requires considerable skill, and equipment both for transporting and erecting. In this work the Japanese are very skillful even with the use of crude tools (though it should not be supposed that Japan is not modernly equipped with mechanical devices). Japan, hundreds of years ago, performed engineering feats which were very remarkable. Among

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these was the building of the palace walls and moats in Tokyo, Osaka, Nagoya and other places. Some of the mountain roads and tunnels built long ago and existing today are quite unusual, considering the time they were built. The people therefore developed a high degree of skill in civil engineering, and in masonry construction which has made them very adaptable to handling mechanical equipment, though they have not yet attained the high degree of skill in this work they have in civil engineering work.

Japan like England is a maritime nation and from time immemorial her men have been trained in seamanship. They are therefore adept in handling ropes etc., so when it comes to lashing material and transporting over difficult places, the workmen can usually be relied upon to take care of this very well. In fact, the average workman is sometimes more skillful at this than the average American. In the erection of buildings, all scaffolding is made up of light round poles in lengths of 10 to 20 or even 30 feet. These poles are not nailed together but lashed by rope, and it is no unusual thing to see a new building five stories or more in height, surrounded by such scaffolding. While perhaps taking a little longer to construct, the absence of nails permits re-use of the poles, so that they form a permanent stock of the construction company.

### OLD AND NEW TRANSPORTATION METHODS INTERMIXED

Much man power is still used for transporting material and sometimes even very heavy loads are pulled over rollers by men or women. However, the large power

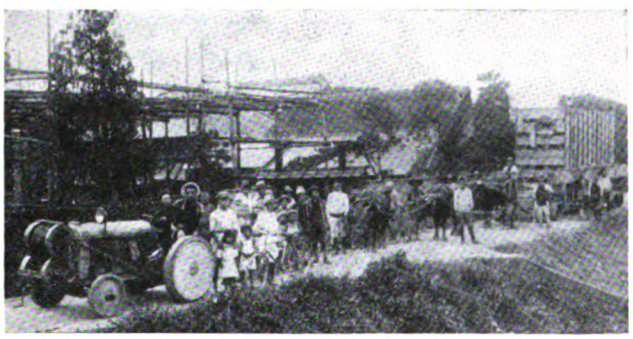

FIG. 5—PRIMITIVE AND MODERN TRANSPORTATION OF ELECTRICAL EQUIPMENT IN JAPAN

companies often use very modern methods of transportation, sometimes building miles of private railway lines. Nippon Denrioku K.K. has a project under way which includes the building of three power houses on the same river, the first of which is now being constructed. For this project they have a well constructed narrow-gauge line which the writer understands has already cost about $1 500 000 for six miles. This has been electrified and in the first six miles there are 30 tunnels, some short but some being as much as quarter of a mile long. These tunnels, of course, have to be large enough to transport the heavy material, there being a headroom of about 12 feet. The roadway is closed during the winter, as it is then covered by from 6 to 15 feet of snow. Due to snowslides, the overhead trolley work and so forth is badly damaged each winter and must be repaired in the Spring.

Aerial transportation by traveling cable is also used to a considerable extent on the larger construction jobs, particularly for the transportation of cement and gravel for construction of dams and masonry structure. The Tokyo Electric Light Co. recently completed the build-

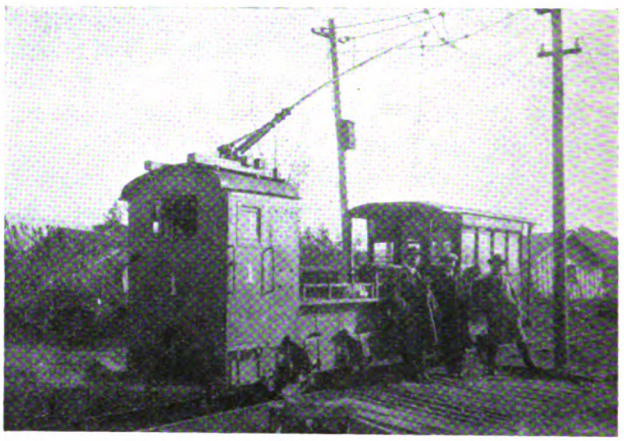

FIG. 6—LOCOMOTIVE AND PASSENGER CARS USED ON TOKYO ELECTRIC LIGHT COMPANY CONSTRUCTION RAILWAY

ing of two power stations known as No. 3 and No. 4 Inawashiro, and all gravel was transported from the river bank at a distance of about four miles by aerial cable.

Inside the power houses modern facilities are provided for carrying on work. Cranes of ample lifting capacity are installed and the general type of construction is very similar to American practice.

The Japanese workman as a rule is very industrious, and can generally be relied upon to do his work to the best of his ability, as he takes a personal interest and pride in his job. The work, however, as a rule is not planned for quick execution and consequently the period of construction is sometimes longer than it would be in America. There is a noticeable absence of the "drive", "drive", "drive" which is so much in evidence on American construction jobs. This means lessened efficiency but also saves everybody's nerves, as the job of building a new power house appears to be a more placid proposition in Japan than America.

### AMERICAN METHODS PREDOMINATE

American practice is more evident than any other in the electrical field in Japan. There are several reasons for this, in spite of the fact that general influence in other fields was more distinctly European. First the development was early in high-voltage transmission. This had been developed to a greater extent in America than Europe, and the early problems met by Japanese engineers had already been solved practically in America. Second the general electrical development was more advanced in America. Third, the war threw Europe far behind in development. America on

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the other hand, while very busy, was able, soon after the war, to get her manufacturing on a highly efficient basis.

As the Japanese language is deficient in technical terms, a very large number of such terms in English have been adopted without changing into the Japanese language, so that technical conversation between electrical engineers always contains many English words. An English speaking engineer, by knowing only a small amount of the Japanese language, can get around the country (even in the mountains) quite satisfactorily, though he will not be able to converse generally. At the power houses, of course, the Japanese engineers all know a certain amount of the English language, as they have studied this for a number of years, particularly those who have attended technical schools. Engineers of other than English-speaking countries find it almost necessary to know English thoroughly.

While the railways are government operated and owned, most of the electric power is generated and supplied by large public utilities the same as in America. Rates vary, of course, according to the class of service, but generally compare quite favorably with rates in America.

Electric lighting is quite universal, even small hamlets being supplied with electric power. In fact, it is probably as widely distributed as in America.

Until recent years the steam station development was considerably behind the hydro-electric development, but with the large and steady demand, shortage during the winter months has become acute and has led to the installation of a number of steam stations. Some of these are operated continuously where the power demand has exceeded the supply of hydro-electric power. However, generally speaking most of the systems of today could handle more load than they have at the present. Therefore most steam plants are shut down or lightly loaded for the major portion of the year. If the water supply is especially good some steam plants are not operated from one year to the next. At the same time the load demand is growing so rapidly that extensive developments are always under way.

### GOVERNMENT PRESCRIBES TESTS

There is one radical difference between American and Japanese practice and this is the government supervision of engineering features. What is known as the Department of Communications of the government has complete authority with regard to government rules and regulations. As the name of this department indicates, its chief work, at least at first, was the control and operation of the systems of communication, the government owning all telephone and telegraph lines.

All power stations are required by this department to be given a final test in the presence of an inspector before they are placed into operation. They also prescribe what tests the apparatus shall undergo. The Japanese name for the Department of Communication is "Teishinsho" and this is the name applied to the test and rules laid down by this department. All power companies therefore, before placing a new station in operation must make a final test in the presence of and under direction of these inspectors. Teishinsho rules with regard to electrical apparatus are quite different from A.I.E.E. rules and, while sometimes not so strict, the longer duration of the test required is not so desirable from the point of view of deteriorating effect on insulation. The usual Teishinsho rule for overvoltage test is 150 percent of the normal rating for a period of 10 minutes, but in the case of high-voltage grounded circuits the test is much lower. For the 154 kv grounded neutral, the test is 167 000 volts for 10 minutes.

Inasmuch as Teishinsho has been primarily interested in communication lines, their rules apparently have been made from this point of view, and sometimes this has caused change in practice in the power field from the American standard. For instance, in America, high-voltage systems are now almost universally operated with the neutral dead grounded. In Japan, on the contrary, while operating with neutral grounded, a single, fairly high grounding resistance is required by Teishinsho in order to prevent induced voltage in nearby telephone lines on occurrence of ground faults. In other word, the responsibility lies with the power company to protect nearby telephone lines rather than the communication department arranging proper protection by keeping telephone lines at a sufficient distance, or by other means. This has made it very difficult to protect such power systems properly by relays, as the dependable operation of such relays depends upon sufficient ground current flowing to insure operation. Such difficulties on the part of the power companies have led them to urge change of the government regulations to permit the use of more and lower value resistances

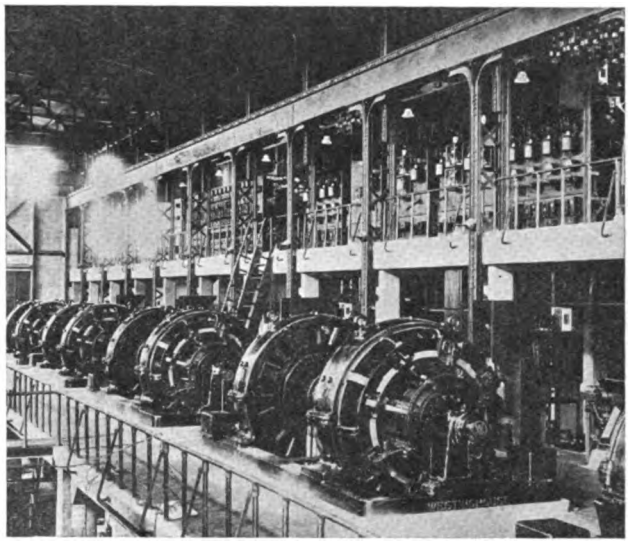

FIG. 7—A 10 000 KW SUBSTATION OF THE JAPANESE GOVERNMENT RAILWAYS

Supplying 1200 or 1500 volt direct-current from synchronous converters. Automatic switching equipment is used.

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or the use of a dead grounded neutral. It appears as though their efforts will be successful. Recently some of the power companies have been allowed to ground their neutral through resistance at both the power station and substation end, and it is expected that permission may be granted in the near future to dead ground the neutral.

With long and high-voltage transmission lines, which are used so generally, some companies have at times experienced trouble with the system stability and some attention has been given to this problem. In the purchase of new machines, the factors affecting stability are given special attention and the results of the experiences and study along this line in America have been watched with interest. As far as the writer could determine, little trouble with stability has been encountered on account of lines operating near the load limit. Rather, instability has occurred only due to abnormal conditions as at times of switching operations or line faults. These troubles have also led to more careful consideration of voltage regulator operation.

Due to early inexperience in handling such expensive and highly complicated machines in large power stations or substations, the maintenance has not heretofore been the equal of that in America. This, however, is a passing phase and the problem of proper maintenance of equipment is given much thought and study. The size and complexity of the power systems and the generally very satisfactory service given is evidence of the success today of Japanese engineers in the electrical field. The average foreign engineer visiting Japan for the first time is generally astonished at the tremendous strides Japan, in but a few years, has made in this direction.

Another point of much interest to the writer has been the study of the characteristics of the people from the engineering point of view. The Japanese are a very energetic, studious people, eager to go ahead and willing to take chances which sometimes look risky but often prove quite successful. These very characteristics are what has advanced them so rapidly in the electrical field. They have been ready and quick to adopt the best foreign practice and, being very studious by nature, they have been able to put into successful operation a great deal of highly specialized machinery.

They have also been rapidly developing their own manufactures. The most successful manufacturers are those who closely follow foreign practice. By agreement the Japanese Companies make use of the foreign designs and even have instructing engineers lent from the foreign companies for several years. In this way the latest designs are available with the minimum of development expense. So far, the designs closely follow those of foreign manufacturers, which is to be expected under such a plan, and there has been but little original work done. It will be interesting to note, however, the trend of design as the domestic companies' engineering departments become more highly developed, and whether real contributions to engineering knowledge will be made by these companies. It is hardly to be expected, however, that they will be able to achieve the results obtained by some foreign companies as such development is largely the result of extensive research work facilities which are as yet largely lacking in Japan.

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# Testing Insulation with High Frequency

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There has been a growing conviction that specifications or methods for testing insulation of electrical apparatus have not been such as to insure satisfactory operation in service. This has resulted in requests for more severe tests, and also resulted in a search for other methods of test that would determine insulation properties not covered by the existing tests. The method of test described here gives a comparative simple, yet remarkably thorough means of determining insulation conditions. This new test bids well to take much of the guess and chance out of insulation testing.

A NEW test has been developed which makes it possible to test completely the insulation of electrical apparatus. It has been found that by applying a single-phase, high-frequency current directly to the winding the location and extent of any weakness may be disclosed without destroying either the defective part or adjacent parts. The method is applicable to any insulated circuit, be it a single coil or a completely wound machine, regardless of voltage. This test, though of great importance, is intended to supplement rather than replace the regular insulation or ground test.

This new method, shown in Fig. 1, tests the internal insulation between turns and layers and phases with the same corresponding completeness that the customary ground test shown in Fig. 2 does to the external shell of insulation which insulates the winding to ground. The A.I.E.E. specifications require that the external shell of ground insulation be able to stand a voltage of 1000 volts plus twice line voltage from the winding to the iron core or frame. The high-frequency test makes it possible to apply a voltage across the terminals of an entire winding or any part of it that will test to the same degree the internal insulation on the turns or layers and the various circuits comprising it, as has been done to the external insulation by the customary ground test.

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Heretofore, it has been possible to test thoroughly only a part of the insulation.

### THE PRINCIPLE OF OPERATION

A very high voltage can be applied to any winding if the frequency is sufficiently great. The voltage drop due to the inductive reactance is $E = 2\pi fLI$ where $f$ is the frequency in cycles per second, $L$ is the inductance in henries, and $I$ is the current in amperes. For example, a 15-turn circular coil with a 12-inch diameter having a direct-current resistance of 0.1 ohm and an inductance of 0.001 henry would have approximately the following voltage across its terminals with 10 amperes in the circuit:

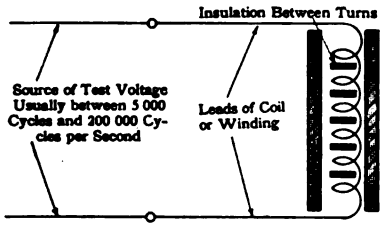
Insulation Between Turns
Source of Test Voltage Usually between 5 000 Cycles and 200 000 Cycles per Second
Leads of Coil or Winding

FIG. 1—CONNECTIONS FOR HIGH-FREQUENCY TEST

1 volt with direct current
4 volts with 60-cycle alternating current
4000 volts with 60 000 cycles per second.

It is seen that practically any desired voltage can be placed across a coil or a winding if sufficiently high frequency is available.

A frequency between 10 000 and 200 000 cycles per second is most often used for individual coils and 5000 to 100 000 cycles per second for wound apparatus. The voltage is applied by connecting the two leads from the high-frequency apparatus directly to the terminals of a partially or completely finished coil or winding.

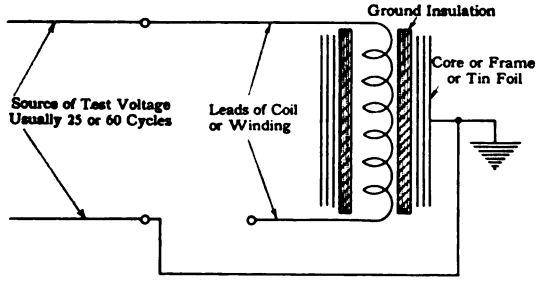


FIG. 2—CONNECTIONS FOR THE CUSTOMARY GROUND TEST

The principle by which the damped high frequency is produced is quite simple. The condensers placed across the secondary terminals, as in Fig. 3, are charged, as shown in Fig. 4, during the first part of each alternation of the 60-cycle current until the breakdown voltage of the air-gap is reached. An oscillatory discharge then occurs between the two rotating discs, which fully discharges the condensers before the beginning of the next half cycle. The frequency of discharge is according to the law,—

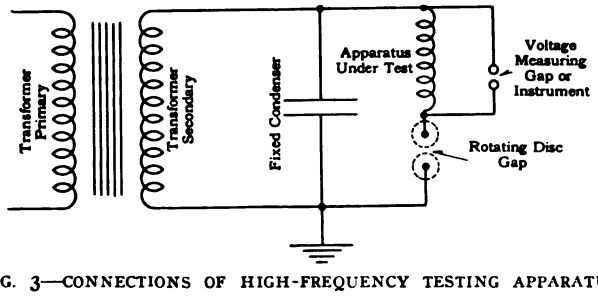


FIG. 3—CONNECTIONS OF HIGH-FREQUENCY TESTING APPARATUS

$$f = \frac{0.159}{\sqrt{LC}}$$

now so well known by radio enthusiasts. Thus, with a 60-cycle impressed voltage there are 120 trains of these damped high-frequency oscillations each second of test. The air-gap spacing is changed at will by moving one of the rotating discs. The larger this air-gap, the higher the voltage. These discs are rotated so as to reduce pitting caused by the arcs.

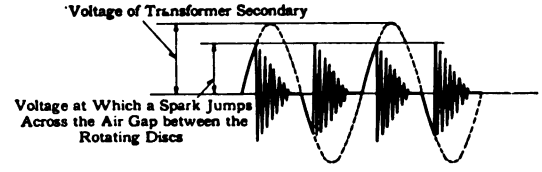


FIG. 4—THE DAMPED HIGH-FREQUENCY VOLTAGE

### THE DETECTION OF DEFECTS

A further important development in connection with this high-frequency test has been that of accomplishing a method of detecting and locating any insulation breakdown without waiting until it burns its way through the insulation and is discovered by smoke or flame. This is accomplished by watching a milli-ammeter connected in a special radio receiving set, shown schematically in Fig. 5.

When high frequency is applied to the apparatus under test, it sets up an alternating electromagnetic field of a particular frequency as determined by the formula $f = \frac{0.159}{\sqrt{LC}}$ in a manner similar to a radio transmitter. If a short-circuit occurs in the winding, the wave length and frequency will be changed, and the strength of the radiated field is reduced, which fact is registered by the milli-ammeter.

Pictures of these test sets in operation are shown in Figs. 6 to 11. The construction is simple and rugged, with no parts that can easily get out of order. The operation is simple, after a certain amount of experience is had. Fifteen or twenty seconds are required for testing one coil or group of coils, and usually a couple of minutes for a complete winding. Instead of the coil shown under test in Fig. 7, there could be a coil for any motor or generator regardless of size or voltage. Field coils, relay coils, transformer coils —in fact any kind of coil can be tested by this same test set.

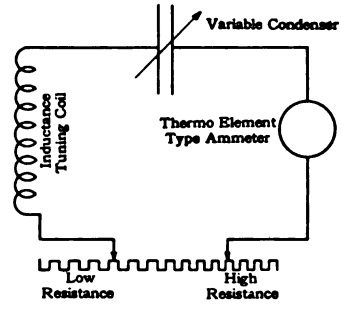


FIG. 5—CONNECTIONS OF INSULATION FAILURE DETECTING APPARATUS

Although this method has proved extremely useful and necessary in the testing of coils, it is even more important in its application to completed windings. It can be used on three-phase as well as single-phase stators and rotors of induction motors, alternating-cur-

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rent generators, induction regulators and direct-current armatures and fields.

APPLICATIONS FOR THE TEST

This method of insulation testing was first applied commercially in the testing of induction regulator coils. The results were so satisfactory that the test was extended to the wound regulators, both stators and rotors of single-phase and three-phase regulators. Thousands of induction regulator coils for machines of all voltages up to 14 000 volts and hundreds of wound primaries and wound secondaries are now being tested each month with high frequency. Up to this time more than 100 000 induction regulator coils have been tested and about 10 000 complete primaries and secondaries. Thousands of other coils for induction motors, turbogenerators and synchronous motors, and hundreds of direct-current armatures and miscellaneous wound apparatus are being tested monthly.

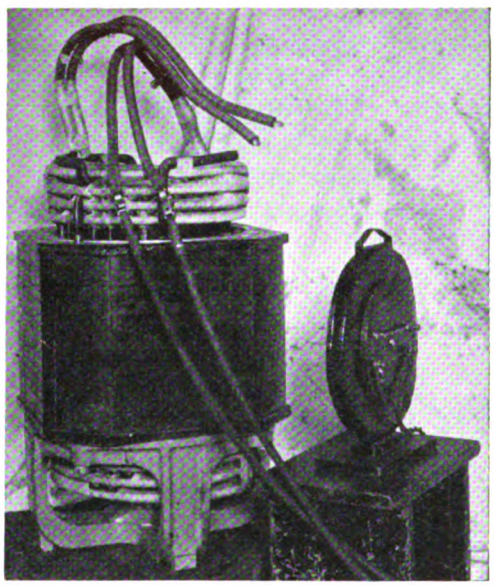

FIG. 6—TESTING THE SECONDARY OF A 57 KV-A, 2200 VOLT, SINGLE-PHASE INDUCTION REGULATOR WITH CURRENT OF 100 000 CYCLES PER SECOND

As the secondary winding operates in series with the line and all line surges must pass through it, this winding is being tested with a voltage more than 100 times the normal volts per turn. The tuning coil which is in series with the meter of the detecting device is about 12 inches from the iron of the stator core.

ADVANTAGES OF USING THIS TEST

There are a number of advantages of using this test. The insulation is known to have been given a thorough test. Further this test approximates the operating conditions of opening and closing switches and of the many other surges occurring on the lines. It is also an effective check on both the design and manufacture of the insulation. Numerous cases could be cited to show where faulty or damaged materials or defective workmanship has been discovered and corrected; also processes of manufacture have been altered and windings redesigned because the high-frequency test showed not only the inadequacy in some cases and the unnecessarily liberal margin in others, but also showed the exact location of the weakness and the probable cause. One of the decided advantages is that it shows the exact location of the defects, in contrast to the usual occurrence in service in which all evidence of the cause has been destroyed when an insulation failure occurs. It has also been found that the running of a machine for a limited time at its rated voltage and current does not necessarily disclose a short-circuit caused by a copper to copper contact. It should be noted that the high-frequency test not only discloses short-circuits caused by actual copper to copper contact, but also shows weak or damaged insulation in which there is no such actual contact.

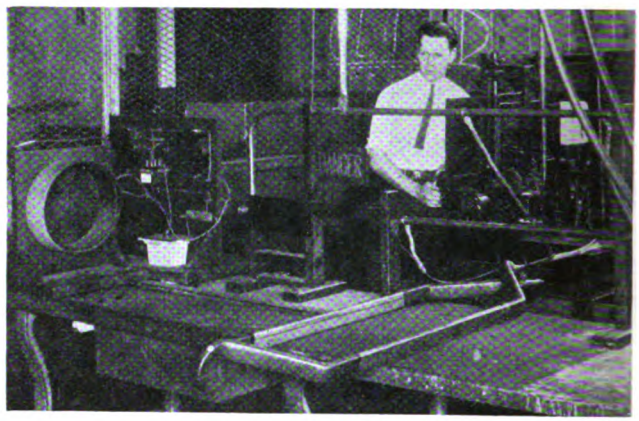

FIG. 7—TESTING A COIL FOR AN 8750 KV-A, 11 000 VOLT SYNCHRONOUS GENERATOR WITH CURRENT OF 200 000 CYCLES PER SECOND

The operator is raising the voltage with his hand on the wheel that regulates the spacing of the rotating spark gap, and he is observing the meter of the detecting device that indicates whether the coil is good or short-circuited. The tuning coil of the detecting device, which corresponds to an aerial, can be seen several feet away from the coil under test.

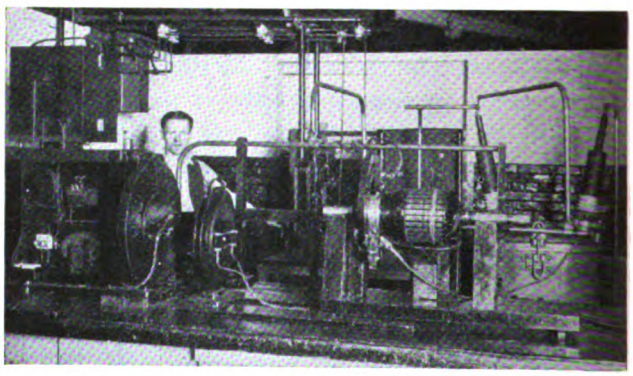

FIG. 8—A TYPICAL STANDARD RAILWAY MOTOR ARMATURE RATED AT 35 HP, 600 VOLTS

Being tested with high frequency. As this is a four-pole armature the voltage is applied at two places on the commutator 90 degrees apart corresponding to the brushes. The armature is rotated one revolution or more and if the winding is good the meter of the detecting device will maintain a steady reading, but if there is any short-circuit or defect, the meter will fluctuate up and down four times for each revolution, one for each pole.

TESTS RESULTS

The test results show that when any line of coils or wound machines are tested, the percentage of failure

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will usually be about five percent at first, but soon will be gradually reduced to one percent. Although the average is about one percent, there are many designs on which this percentage is one-fourth of one percent and other cases where a whole set of coils failed. The great reduction in the number of coil failures was accomplished by correcting the cause of the trouble, usually evident upon a thorough examination. However, if these coils had not been rejected on account of the high-frequency test results, all of the coils would have been used, as none had any defect that could have been discovered by any other method.

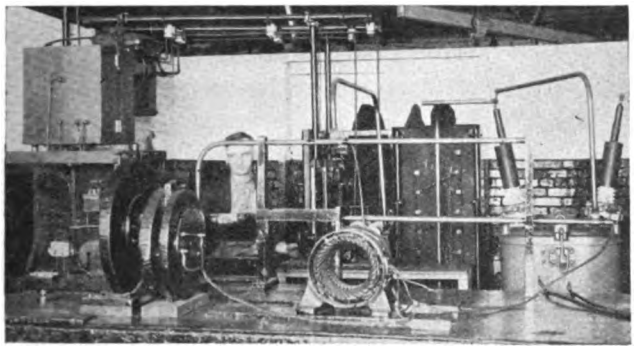

FIG. 9—FIVE HORSE-POWER 440 VOLT, THREE-PHASE INDUCTION MOTOR

Being tested with 2500 volts high-frequency current across two of its three leads. The tester is closely observing the meter of the detecting device, as well as the special crest voltmeter used for measuring the damped high-frequency voltage.

A record of the complete windings that have been tested show similar percentages. However, it is not to be inferred that all the faults detected by this test would have resulted in service failures. The applied test has purposely been made severe in order to be certain to weed out all weaknesses of this class.

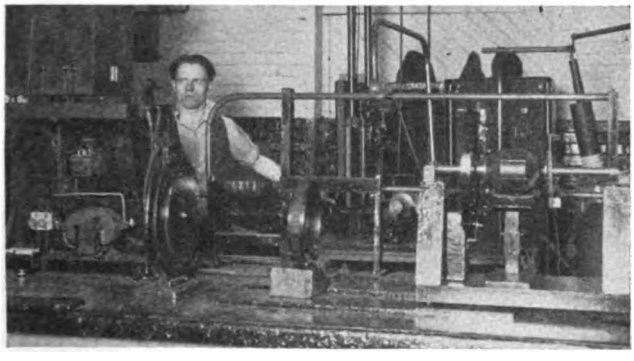

FIG. 10—ILLUSTRATING THE LOWER RANGE IN SMALLNESS REGARDING SIZE AND RATED VOLTAGE THAT CAN BE TESTED WITH THIS HIGH-FREQUENCY VOLTAGE

This is a one kw, 36 volt, direct-current armature, being tested at 1000 volts. The voltage is applied at two points on the commutator, spaced 180 degrees apart, the same as the brushes of this two-pole armature.

Induction regulators are the only type of apparatus tested with high frequency which has been in service for a sufficient period of years to secure a measure of the improvement obtained. There has been a distinct improvement in these machines from the service standpoint. Whereas, there was a considerable number of failures before high-frequency testing was started, the number of failures since then has been negligible.

### THE NEED OF THIS TEST

High-frequency testing detects imperfections in materials and workmanship, checks the insulation design and the processes of manufacture. It insures that proper and adequate insulating materials are in their correct places and are not damaged and that no harmful foreign materials are present. It checks up such features as the elimination or accumulation of moisture and the thoroughness of impregnation, undue mechanical pressure at any point and the ability of the materials to stand the mechanical operations of coil construction, and whether the materials are sufficiently uniform.

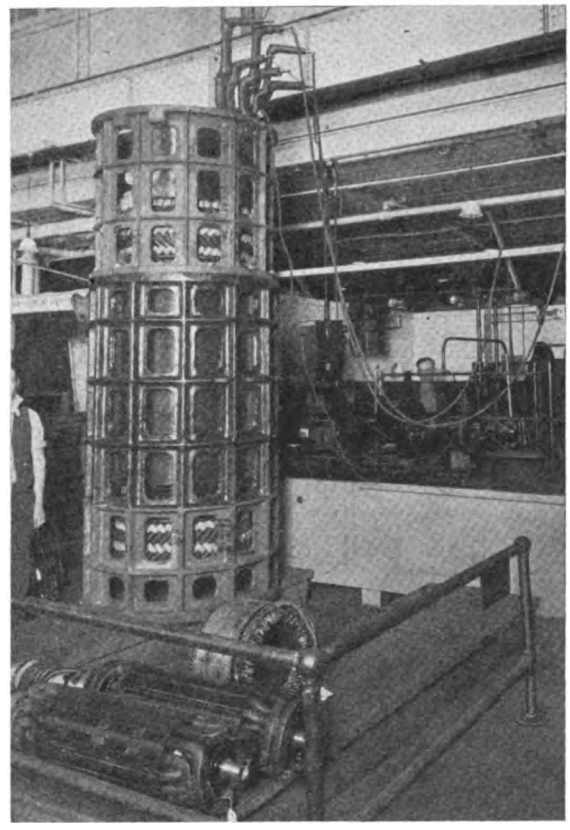

FIG. 11—THREE-PHASE INDUCTION REGULATOR RATED AT 1080 KV-A, 12 500 VOLTS

Being tested with high frequency. This shows the ability of this set to test very large or high voltage apparatus, and also to test three-phase as well as single-phase windings. Two primary windings of smaller size regulators and a three-phase induction motor which have been tested can be seen.

Any or all of the above conditions may exist, but they can not be detected or discovered without the aid of high-frequency testing as they are hidden from view and visual inspection is useless.

One real merit of high-frequency testing is that the cause of the failure can invariably be ascertained. The reason for this is that the current is relatively small and, therefore, the arc is of only such intensity as to burn out the weak insulation without burning the copper. When a machine fails in service the damage is usually severe and wide spread, and the cause can seldom be accurately determined.

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# Power-Factor Rate Clauses

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Massachusetts Institute of Technology

A HIGH power-factor is advantageous to any power system, whether it is a city system, or a widespread transmission system. A practical comparison is here made of different methods in use for securing improvement in power-factor on power systems.

*Method I*—The most effective method, for a given cost, is to influence customers to choose synchronous rather than induction motors by making a change in the energy bill directly proportional to the kv-a of synchronous machines installed and kept properly adjusted. A suggested rate is a discount of five cents per month per kv-a of synchronous motors.

*Method II*—Another, and more common method, is to impose a penalty on customers having a low power-factor, by increasing the bill in the proportion that a desired value of power-factor, such as 80 percent, is higher than the actual power-factor.

*Method III*—A third method is to make use of a schedule of penalties for low power-factor which are similar to those of the preceding paragraph, but considerably smaller, as indicated in Table I.

Other methods of writing rate clauses, some of which are more complicated, give substantially the same results as one or other of the above methods, so far as power-factor is concerned. For example, if the percentage of penalty is calculated according to Method II, but applied only to the demand charge part of the bill, the net result will be a penalty approximately as large as by Method III. This is more commonly used in the United States than Method II.

Certain disadvantages of the second and third methods have been observed after practical experience during a number of years. The penalties produce comparatively little improvement in the power-factor of the entire system. They make changes in the equipments of only a few of the customers, namely, those of very low power-factor, and such changes are made at a high cost per kv-a. The penalties do not result in the installation of synchronous motors in nearly as many cases as there are obvious opportunities for them. It is not easy for a customer to determine the reduction in penalty to be expected from the installation of a given synchronous motor, and so it is harder to justify the extra cost of that type of motor. After the local power-factor has been increased to about 85 percent, perhaps by installing only one synchronous motor, there is little or no incentive to install any more of them, though there may be several good opportunities.

Another disadvantage of Methods II and III is the difficulty in explaining to non-technical customers what power-factor really is and why they should pay a penalty for low power-factor. This is not necessary with Method I.

**It is a trustworthy principle in connection with the engineering and economic relations of two parties, that the best arrangement of apparatus, in the long run, is that which would be used if one company took the place of both parties and owned all the apparatus. It is noticeable that when a company using electric power has its own generating station, it installs synchronous motors wherever opportunity offers.**

METHOD I AVOIDS DISADVANTAGES OF METHODS II AND III

The first method of improving power-factor, namely, by means of a discount proportional to the kv-a of synchronous motors installed, overcomes the disadvantages of the other methods. There are power companies which have in this way obtained the installation of large numbers of synchronous motors. Some of their customers have all their large motors of the synchronous type. The power-factor of the power company's total load is close to unity, and it is a matter of record that low power-factor has ceased to be a problem. Such power companies are in marked contrast to others on whose lines are many induction motors of good size, but not a single synchronous motor, and whose low system power-factor is a serious handicap. Evidently a lesson for the entire electrical industry is to be learned from the systems which have succeeded in arriving at high power-factor.

Many companies, both those supplying city systems and those having extensive transmission line networks, have found it profitable to install synchronous condensers. A company which can afford to install synchronous condensers can afford to pay the bonus previously mentioned of approximately five cents per month per kv-a of synchronous motors. The bonus is subject to the provision that each synchronous motor rheostat be set to give the largest safe value of field current, and then not changed from that setting no matter what changes in load occur. A comparison between an induction and a synchronous motor should not be made at full load, but at the average load, which will be about ¾ load. Taking the synchronous motor kv-a rating as 100 percent, the lagging reactive current of the induction motor will be about 50 percent. A synchronous motor of 100 percent power-factor rating, operating at ¾ of its rated mechanical load, and with maximum safe field current, will take approximately 25 percent leading kv-a. To choose a synchronous motor instead of an induction motor, therefore, represents in an average case a total increase in leading kv-a of three-fourths of the synchronous motor rating. In other words, a

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100 percent power-factor synchronous motor is about three-fourths as effective in improving power-factor as a synchronous condenser of the same rating. The synchronous motors are more scattered than synchronous condensers are likely to be. There is diversity in the loads of the synchronous motors, some operating at partial load and leading power-factor at the time of the peak load of the system.

The capital cost of synchronous condensers in ordinary sizes, installed, would be about $8.00 per kv-a. The annual cost of interest, depreciation, insurance, repairs and operation would be at least 15 percent, making $1.20 per kv-a per year or 10 cents per kv-a per month. Taking three-fourths of this for the synchronous motor gives 7.5 cents per kv-a per month, which is considerably greater than the suggested discount of 5 cents per kv-a per month.

From the customer's point of view, it is desirable to estimate what percentage return on the extra investment the discount represents. The excess in cost of synchronous over squirrel-cage induction motors is about $3.00 per kv-a in sizes around 150 hp, about $2.00 for 200 hp and down to $1.00 or less for larger sizes. Taking $2.00 per kv-a as an average value, the discount of 60 cents per kv-a per year amounts to a return of 30 percent on the extra investment. This will be reduced by only a small fraction by reason of the additional losses due to operation with strong field current, in ordinary cases.

TABLE I—POWER FACTOR PENALTIES

| Power-Factor for Month Percent | Penalty according to Method II, Percent | Penalty according to Method III, Percent |
|---|---|---|
| 100 | 0 | —5 (bonus) |
| 90 | 0 | —2 (bonus) |
| 80 | 0 | 2 |
| 70 | 14 | 8 |
| 60 | 33 | 18 |
| 50 | 60 | 33 |

N. B.—Sample derivation of penalty according to Method II: $\frac{80}{70} = 1.14$, $100 \times 0.14 = 14$

### DISCOUNT IS SMALL PORTION OF POWER BILL

It is of interest and considerable importance to see what a small percentage of the power bill this suggested discount is in order to compare it with usual power-factor penalties. Assume that the synchronous motors operate at 15 percent load factor and 80 percent power-factor, and that energy costs one cent per kw-hr. The energy bill for a month will be 86 cents per kv-a of motor rating. The discount of five cents is six percent of the energy bill of the synchronous motors themselves, and three percent of the total energy bill, assuming that the synchronous motors make up half the load. The above small percentage would be smaller still if the cost of energy and the load factor were higher. These percentages are to be compared with the much larger percentages of the penalties shown in Table I.

A power-factor of 60 percent is frequently encountered, and penalties of 33, or 18 percent of the energy bill, are actually imposed. Yet it has been shown that this would have been forestalled by an investment in synchronous motors, corresponding to less than three percent on the above basis. While in many cases the penalties are paid because of lack of knowledge that a choice of one or more synchronous motors would have prevented the imposition of the penalties, yet often the power consumer uses such small motors, even though in large numbers, that there is no opportunity for the installation of the synchronous type, which should have ratings of at least 50 hp, and usually 100 hp. Where large induction motors are already installed, the cost of exchanging them for the synchronous type is much greater than the cost of choosing synchronous instead of induction motors for new installations. In such cases, the energy supply company should realize that a small percentage discount applied directly to synchronous motors has in some localities secured enough synchronous motors to bring the system power-factor close to unity, and that these motors were sufficiently scattered so that the expenses and disadvantages which led to the power-factor penalties largely disappeared. There might be slight disadvantages close to installations of very large numbers of small induction motors, but these would not produce the usual power-factor problem. It is therefore a better policy for the power company to secure the installation of a generous number of synchronous motors by such customers as can install them, and not to discourage unduly the use of electricity by heavy penalties on the other customers.

It is a trustworthy principle in connection with the engineering and economic relations of two parties, that the best arrangement of apparatus, in the long run, is that which would be used if one company took the place of both parties and owned all the apparatus. Thus it is noticeable that when a company using electric power has its own generating station, it installs synchronous motors wherever opportunity offers, even though some departments are made to have unity or leading power-factor.

It is sometimes stated that since the greater part of the costs of supplying electrical energy are proportional to the kv-a, that is, to the power-factor, customers should pay in that proportion. This would mean that they should pay penalties for low power-factor according to Method II. However, it is a generally accepted business principle that customers should not pay continuously for a wrong condition in proportion to the damage done, but rather in proportion to the cost of curing the condition and preventing the damage, if the latter cost is less than the cost of the damage.

Power-factor should be corrected in the cheapest possible way. Power users who cannot install synchronous motors often spend five or ten times as much per leading kv-a in order to obtain power-factor improvement as those who can use synchronous machines. It is much cheaper to correct power-factor wholesale than retail. By means of Method I, the power-factor is corrected wholesale to a considerable extent, and at the same time the correction is done in scattered locations, which is desirable.

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As an example of how even the most drastic power-factor penalties do not induce a customer to install as many synchronous motors as there is good opportunity for, Tables II and III are shown. These show the average load of a new factory. The power-factors are lower than for the rated load of the apparatus, since they are for the average load.

In Table II only one synchronous motor is used, but as the power-factor is 92 percent, it would not be

TABLE II—TYPICAL FACTORY LOAD WITH INDUCTION MOTOR-GENERATOR SET

| | Kw. | Power-Factor Percent | Reactive Kv-a. |
|---|---|---|---|
| (a) Lighting | 80 | 100 | 0 |
| (b) Induction Motors. | 500 | 75 lagging | —440 lagging |
| (c) Synchronous air-compressor motor | 240 | 80 leading | +180 leading |
| (d) Induction motor-generator set, to supply direct-current motors | 400 | 85 lagging | —250 lagging |
| Total | 1220 | 92 lagging | —510 lagging |

usual for a penalty to be imposed, even where the second method of writing a power-factor rate clause is used. If an incentive to install as many synchronous motors as possible is provided, as by the first method, than a synchronous motor would be specified for the motor-generator set also, and the power-factor would become slightly leading.

A common method of expressing the improvement so produced, and one which forms the basis of many power-factor clauses in contracts, is to say that the customer's power-factor has been changed from 92 to 100 percent. A statement which conveys much better information regarding the cost to the customer and the benefit to the power company is the simple statement that 550 leading reactive kv-a have been added by using a synchronous motor instead of an induction motor for item (d). Power-factor clauses should be written in accordance with this latter statement if they are to secure the greatest benefit to the power companies, and the fairest treatment of the customers. What the power companies really need is a good proportion of synchronous motors on their lines. Accordingly they should make efforts to secure synchronous motors directly and not indirectly. The attempts to obtain power-factor improvement should therefore not be made one customer at a time, but rather one large motor at a time.

## LOOK TO LARGE COMPANIES FOR POWER FACTOR CORRECTION

Many power companies have been trying for a considerable number of years to improve power-factor conditions by dealing with the customers of lowest power-factor, who were small customers or users of small induction motors. These efforts have not produced a sufficient total result, and the average unit cost of the leading kilovolt-amperes which have been obtained has been high, to the customers in actual cash, and to the power company in loss of business. Much larger results can be obtained by turning to the larger customers for leading kv-a, even though the latter already have a fairly high power-factor.

Actual and prospective customers should feel assured that if they install synchronous motors and keep them running to a reasonable extent, they will without fail receive the discounts which represent interest on their extra investment. Accordingly, contract terms designed to protect the power company regarding the time each month that the motors are in service, etc., should be written so as to be in the customer's favor as much as possible. The power company wishes a large number of customers to invest in synchronous motors. It can afford to take the risk that the majority of the synchronous motors will be run most of the time, so as not to implant the fear that the discounts will not be allowed.

An inexpensive and reliable way of measuring the number of hours per month that a motor is in service would be to arrange an ordinary single-phase residence watthour meter to run as a constant speed motor instead of a watthour meter. Then if it is connected across one phase of the synchronous motor, its dial reading will be proportional to the number of hours that voltage has been applied to the motor. Another method would be to make use of an ordinary revolution counter connected to the synchronous motor. A contract provision could specify that when the motor is not run more than a certain minimum number of hours in any month, the discount will not be allowed.

Provision can be made that the synchronous motors will be available to the power company's inspector at any time during business hours. Another clause can provide that the synchronous motor rheostat be set to give the maximum safe field current and never changed from that setting. The fact that an inspector can ask without warning at any time to see the motor is sufficient for the enforcement of this provision. The value in amperes of the maximum safe field current can be obtained from the manufacturer, or by test. If after installation the customer can show that under his operating conditions an excessive temperature on either the

TABLE III—TYPICAL FACTORY LOAD WITH SYNCHRONOUS MOTOR-GENERATOR SET

| | Kw. | Power-Factor Percent | Reactive Kv-a. |
|---|---|---|---|
| (a) Lighting | 80 | 100 | 0 |
| (b) Induction Motors | 500 | 75 lagging | —440 lagging |
| (c) Synchronous air compressor motor | 240 | 80 leading | +180 leading |
| (d) Synchronous motor-generator set, to supply direct-current motors | 400 | 80 leading | +300 leading |
| Total | 1220 | 99 + leading | + 40 leading |

armature or the field is produced, the value of field current can be changed. The provisions for maximum field current at all times will not apply when the field current is controlled by an automatic voltage regulator, since in the latter case the maximum field current will be given when it is most required.

In the case of a group of large synchronous motors supplied from a transmission system, it may not be to the power company's best interest to have maximum field current at all times that the motors are in operation. This might give too much voltage rise at times

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A provision may be incorporated in the contract by which the power company may make requests for adjustment of the field current within certain limits. This has been done in some practical cases.

Static and synchronous condensers and unity power-factor motors can be given the same discounts per rated kv-a as synchronous motors. It would not complicate matters too much if it were specified that the amount of rebate agreed upon for each particular motor would not be changed for a definite number of years, after which the prevailing rates would apply. This would increase a prospective customer's confidence in the rebates, and at the same time would allow the power company to lower the rate of discount offered for new installations from year to year.

A definite rebate per kv-a of synchronous motors, as described under Method I, can be granted without interfering with any other power-factor rate clause, such as Method II or III, which may be already in force. Both methods can be in operation at the same time, if desired.

The total amount of money represented by the discounts under Method I will naturally be considered carefully by a power company. It is obvious that a company which is about to lower its rates slightly in order to increase its volume of business will be in the best position to offer the proposed discounts. It should be remembered that the discounts of Method I are equivalent to a general reduction in power rates of only a fraction of one percent, since only part of the customers will receive them. If these discounts improve the power-factor and make the use of electric power more attractive because of lower net rates and because of better voltage regulation, they will probably be found to be worth while.

### CONCLUSION

In conclusion, a definite rebate in cents per month per kv-a of synchronous motors operated with maximum field current will make a more substantial improvement in power-factor than other rate clauses used, for the following reasons:—

1—The return on the extra investment for a synchronous motor is definitely known in advance by the power user. This helps to justify the choice of the synchronous machine.

2—Power users who already have one synchronous motor and a fairly high power-factor are induced to install more of this type of motor.

3—Power users who have a number of synchronous motors are induced to operate them with strong field current.

4—The necessity of explaining the meaning and expense of low power-factor to non-technical power users is avoided.

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# The Master "Mind" of the Holland Tunnel

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The general problem of ventilation of the Holland Tunnel was discussed by Messers. Bedworth and Dawson in the November, 1927 issue of the JOURNAL; and the special features of illumination by Mr. Atwell in the July, 1927 issue. While complete in itself, no attempt is made in the following article to repeat information given in the previous articles.

AS a bridge is a street over a river, so the twin tubes of the Holland Tunnel are regarded as a street under the Hudson River connecting New York and New Jersey. These tubes were built to relieve the congested condition of traffic on the ferries and to aid in the movement of goods between the two states. The opening of the Tunnel has made it possible to travel between Manhattan and Jersey City within a few minutes, eliminating the inconvenience that was caused by waiting in long lines to board the ferry.

The problems encountered in the construction of this tunnel brought about extensive experimental and research work, as no data was available on such an enterprise. The main engineering problem involved is that of securing adequate ventilation in such long tubes filled with exhaust gases, primarily carbon monoxide, emitted from motor vehicles.

The tunnel consists of twin tubes, one for east bound traffic and the other for west bound traffic. Inside each tube a twenty-foot roadway is built, and on the left side, with the direction of traffic, is a raised sidewalk for use primarily by the traffic police. The alignment of the tunnel is by no means straight, having bends and curves, particularly near the portals. The roadbed slopes from the entrance down to the middle of the river and from this point up to the exit. The cross-section of the Tunnel, showing the roadway and walkway can be seen in Fig. 2, which shows also the method of ventilation.

### METHOD OF VENTILATION

As present day traffic is almost entirely composed of motor-drawn vehicles, natural draft was never considered as a means of ventilating the Holland Tunnel. After a lengthy research period, a transverse or vertical method of ventilation was decided upon. The small arrows in Fig. 2, show the direction of the air currents across a section of the tunnel. From the fresh air duct beneath the roadway, branches lead to an expansion chamber along the curb whose purpose is to reduce the speed of the fresh air. The air passes out of the expansion box to the roadway through an opening which

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is adjusted by means of a steel plate located just above the curb. The ceiling above the roadway contains louvres, spaced equally distant, through which the impure air passes to another duct. Exhaust fans suck this air to a shaft.

There are three sets of fans to each of the seven sections of each tube, each set consisting of blower and exhaust, making a total of 84 fans. Not all of the motors are operated at any one time, as enough are held in reserve for an emergency. The complete ventilation system was designed with the idea of making the Holland Tunnel as safe as any open-air boulevard. To secure this result to the fullest degree, every precaution was taken to prevent any failure of power supply or improper operation of control equipment.

### ELECTRIC POWER SUPPLY

Although one feeder from a nearby generating plant would be sufficient to carry the load of all electrical equipment connected with the Tunnel, the engineers in designing the power layout, in order to insure continuity of service, arranged to have six feeders, three from the Public Service Corporation of New Jersey. Two of the three feeders on each side of the river come from separate generating plants, therefore, four plants would have to be disabled before the power supply would fail.

Each feeder is 13 200 volts, three-phase, 60 cycle supply. The three feeders from the New York generating plants enter at the New York land ventilating building, while the three from New Jersey generating plants enter at the New Jersey land ventilating building. In the land buildings each feeder connects to a three-winding, air-blast power transformer where it is transformed to 2300 and 440 volts as shown in Fig. 3. Through the tie bus any one of the incoming feeders can supply the complete tunnel. For instance, when one New York feeder is called upon to carry the load for the whole tunnel, the New Jersey side is fed through the 2300 volt winding of the power transformer connected with the live feeder. Due to both electrical and mechanical interlocks no incoming feeder can be paralled with another, whether it originates from New York or New Jersey.

### SWITCHBOARD AND LOCAL CONTROL

The control and protective switchboards, for the incoming lines, shown in Fig. 4, are similar for the New York and New Jersey land buildings. The boards in the two river buildings are similar, except that the sections for controlling the incoming feeders are omitted. Each section of the switchboard is composed of a steel cabinet, having a swinging steel door in the rear to provide access to the interior of the cabinet. On the extreme left-hand end of this switchboard are the control switches. indicating lamps and ammeters used in conjunction with incoming lines. The miniature bus gives a single-line diagram of the feeders, and the positions of the control switches correspond to the locations of the oil circuit breakers in the feeders. Each control switch has above it a green and white indicating lamp. When the green lamp is illuminated the circuit breaker is in the closed position. The white lamp has two degrees of brilliancy, the dim light indicating that the breaker has been tripped manually, while the bright light indicates that it has been automatically tripped, due to some fault or failure. A white indicating lamp, located in the miniature bus for each

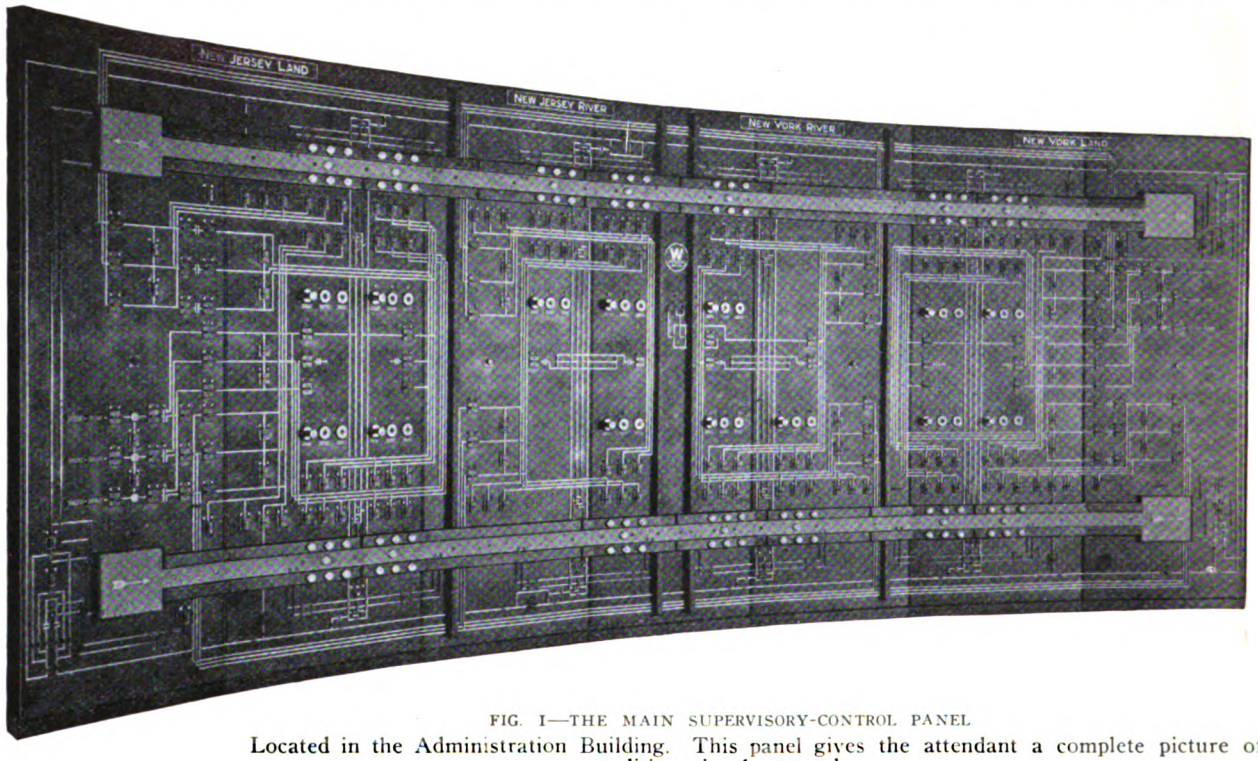


FIG. 1—THE MAIN SUPERVISORY-CONTROL PANEL
Located in the Administration Building. This panel gives the attendant a complete picture of conditions in the tunnels.

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feeder, indicates that there is potential on that particular feeder.

Upon the swinging door in the rear of this cabinet are the interlocking and protective relays. Directly behind this switchboard is another similarly constructed switchboard which contains the protective relays used on the incoming lines. Referring to Fig. 3, the relay protection for one incoming feeder section is as follows:—Oil circuit breakers 1, 2 and 3 have short-circuit protection; they also are tripped by differential

FIG. 2—A CROSS-SECTION OF ONE TUNNEL

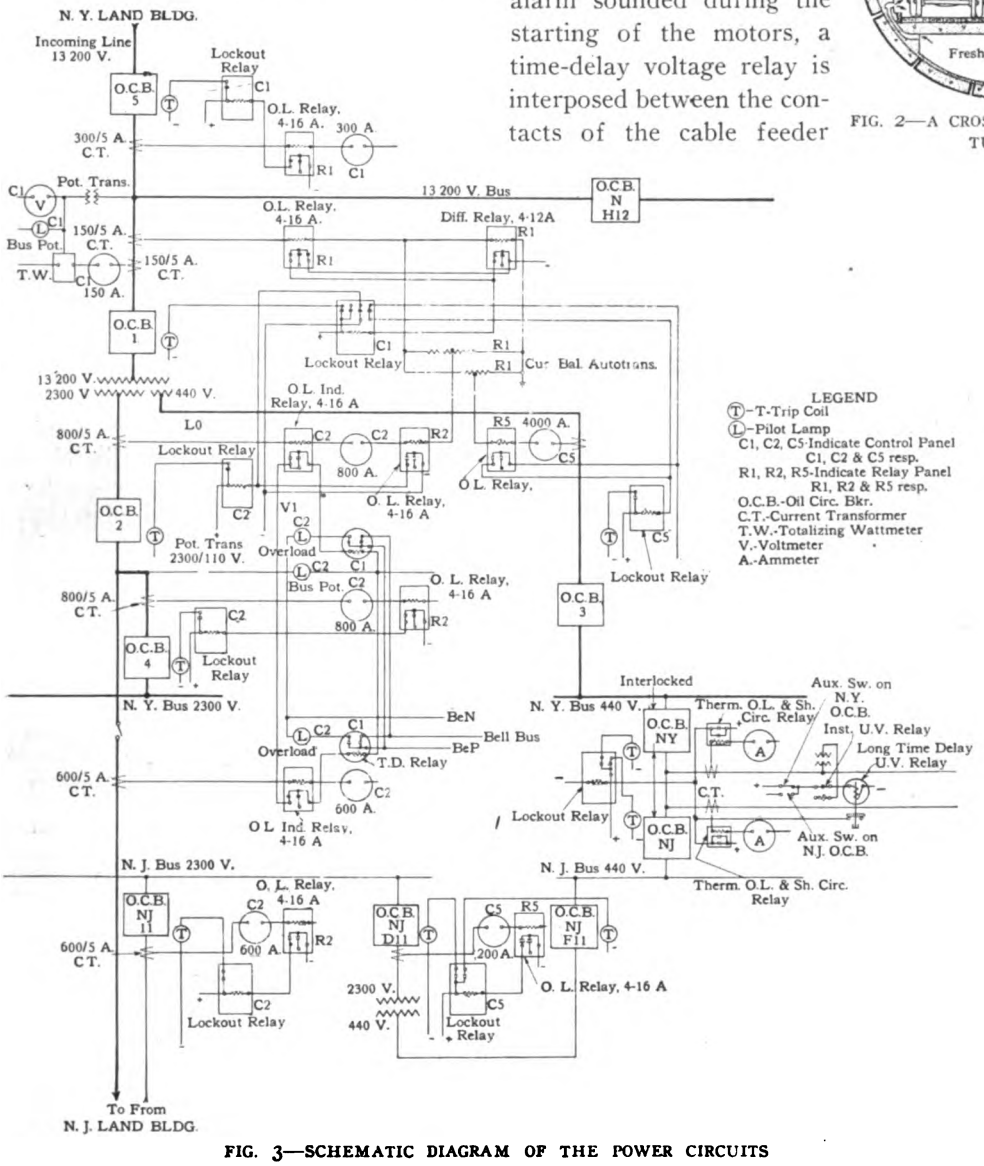


FIG. 3—SCHEMATIC DIAGRAM OF THE POWER CIRCUITS

protection relays used in connection with the main power transformers. Circuit breakers 4 and 5 have only short-circuit protection. Whenever the short-circuit or differential relays operate due to some fault, their contacts operate a lockout relay, whose contact in turn trips the circuit breaker. The lockout relay has several contacts, one of which changes the brilliancy of the white lamp on the control board from dim to bright, indicating an automatic operation; another contact energizing a bell-alarm relay. These lockout relays are of the hand reset type, and when once energized by the protective relay, the operator must reset them before the circuit breaker can be reclosed. In addition to the indicating lamps at the control switches, there are also white indicating lamps which become illuminated whenever the overload protective relays are energized due to some abnormal condition on the 2300 volt feeder cables.

To prevent the white indicating lamps from being illuminated and the bell alarm sounded during the starting of the motors, a time-delay voltage relay is interposed between the contacts of the cable feeder overload relay and the alarm devices. Therefore, no indication or alarm will be given until after a definite time, determined by the length of the starting period of the motors.

### MOTOR SPEED REGULATION

The method of ventilation used requires three different speeds for the fans. Consequently, the motors are of the wound-rotor induction type and speeds are obtained by varying the resistance of the rotor. The three switches grouped together and shown near the bottom of sections 3, 6, 7 and 8 of the switchboard, in Fig. 4, are for speed control. To select a particular

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speed, the key or handle must be inserted in the corresponding switch. To prevent the operator from forgetting to select a speed when he starts up any one of the fans in that particular section, an alarm will be sounded if a speed has not been designated. The speed

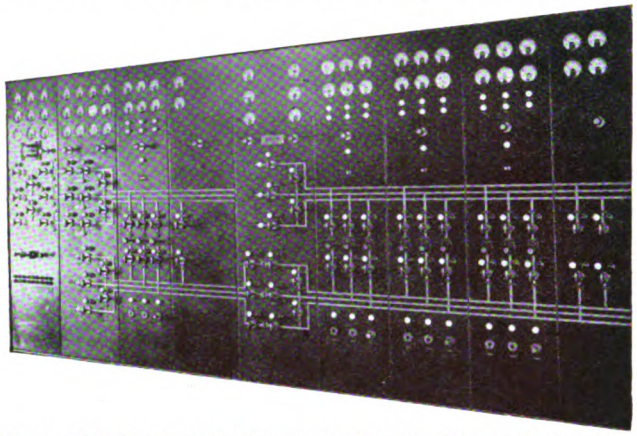

FIG. 4—ONE OF THE VENTILATION BUILDING SUPERVISORY-CONTROL PANELS

equipment consists of contactors with dashpots and a timing relay, all enclosed in a metal cabinet located near each motor. The electric supply for this apparatus is taken from a small distribution transformer located in the same housing as the truck-type circuit breaker, which controls the main power circuit to the particular motor. As the motors can be fed from either the New York or New Jersey bus, the small distribution transformers will be automatically fed from the respective bus.

As previously stated, three fans feed each section of the ducts. One group of speed-control switches is supplied for each section, so that if three fans should be operating at the same time in the one section, all would be revolving at the same speed. This point is plainly shown in Fig. 4. A white indicating lamp is directly above each speed switch; the lamp being illuminated above the switch corresponding to the particular speed selected.

MOTOR CONTROL AND PROTECTION

In the ventilation buildings, the motors, either 2300 or 440 volt, can be controlled from two points; switchboard and local.

On the switchboard, the blower and exhaust motors are treated as a set, Fig. 5. Two circuit breakers, one connected to a New York bus and one to a New Jersey bus, feed each set with a key operated transfer switch between them, as shown on sections 3, 4, 6, 7 and 8 of the control board, Fig. 4. As stated above, the New York bus cannot be paralleled with the New Jersey bus, an interlock being provided on each circuit breaker, so that if one is already feeding the set the other cannot be closed. The control switches have white and green indicating lamps and function the same as the lamps used with the switches for the incoming lines.

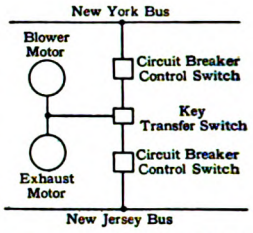


FIG. 5—VENTILATION AND CONTROL UNIT

Above the control switches are two white indicating lamps for each set, one lamp being above the other. The upper one indicates that the blower motor is running and the lower lamp indicates the exhaust. These lamps have two degrees of brilliancy; the bright light

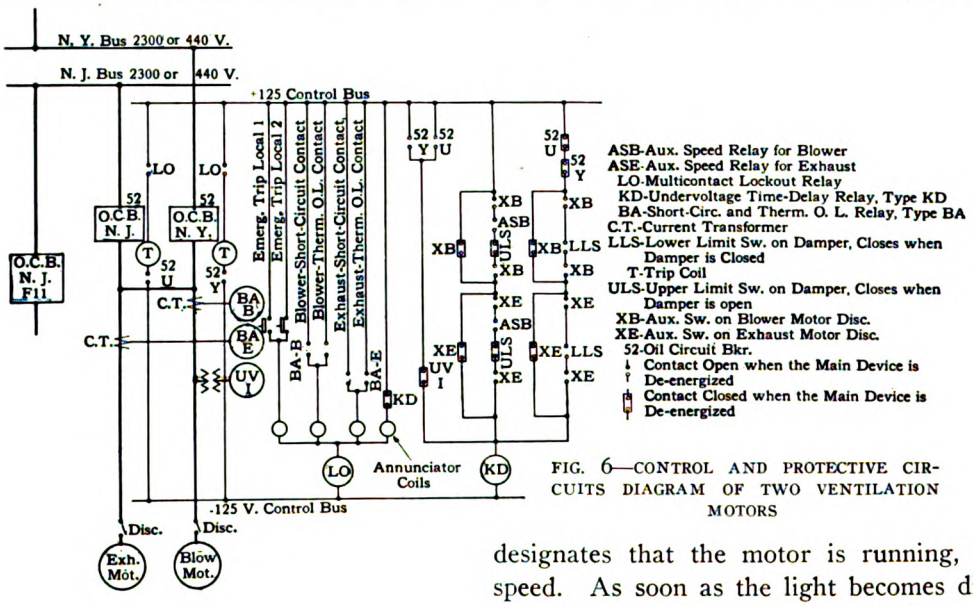


FIG. 6—CONTROL AND PROTECTIVE CIRCUITS DIAGRAM OF TWO VENTILATION MOTORS

designates that the motor is running, but not up to speed. As soon as the light becomes dim, it indicates that the motor is up to speed and that the dampers in the respective ducts (blower and exhaust) are open. The dampers in the ducts are closed when the fans are idle, to prevent back feed of air.

The key-operated transfer switch is used to lock out the switchboard control when the local control is being used. When this switch is in the "off" position, the key to the lock can be removed. The switch cannot be operated until the key is re-inserted and turned.

If the operator wishes to control the fan from its local position, the key is removed from the transfer switch. By going to a cast-iron box, located on a column near the motor, the operator, by inserting the

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key in a similar switch, can perform the same control as was done on the switchboard. In the case of the blower motor, the New York bus is used, and in the case of the exhaust the New Jersey bus is used. In addition to the key transfer switch and the circuit breaker control switch with its indicating lamps, there are located in the local box the same type of speed switches are on the control board, also an emergency trip button and damper cut-out switch. This equipment facilitates making tests on the motor or fan.

The same key used with the transfer switches, also unlocks the speed equipment cabinet and the primary disconnecting switches to the motors. Each set of motors has a different key, so that the interlocking feature is not jeopardized.

Safety on this enterprise has not been limited to the tunnel proper, but also to the control equipment. The key, as explained above, prevents more than one person from operating the equipment, even though there are several control points. Another safety feature is the emergency trip button in the local control boxes. During the test period, should something go wrong or some one be in danger while working around the fan or motor, operating the emergency trip button will de-energize all circuits.

Whether switchboard or local control is employed, the protective features for the motors are the same. Each motor circuit has a thermal overload relay with

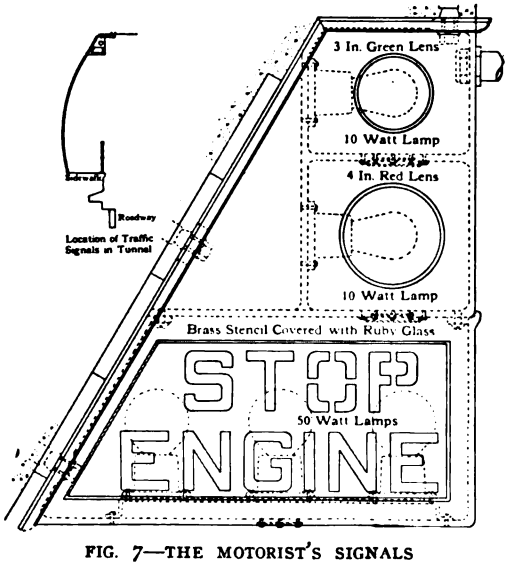


FIG. 7—THE MOTORIST'S SIGNALS

a short-circuit element. In addition to protecting the motor from excessive temperature rise due to overload, the short-circuit element will act instantaneously if a short-circuit occurs.

To protect the motors during the starting and stopping period, against failure of the speed control devices, also should the dampers close while the motors are running, a long time delay under-voltage relay has been supplied. This relay, as shown in Fig. 6, is continuously energized through one of the following circuits:—The auxiliary switch of either closed circuit breaker, and contact of a de-energized under-voltage relay; the contacts of an auxiliary switch on the blower motor disconnecting switch and the exhaust motor disconnecting switch (the disconnecting switches being open); or an auxiliary switch on the blower motor disconnecting switch (disconnecting switch being closed), interlock on the auxiliary speed relay for the blower, upper limit switch on the damper when the damper is closed, and similar circuits on the exhaust motor; or a circuit made by the contacts of both oil circuit breakers that are in the open position, the auxiliary switches on both blower

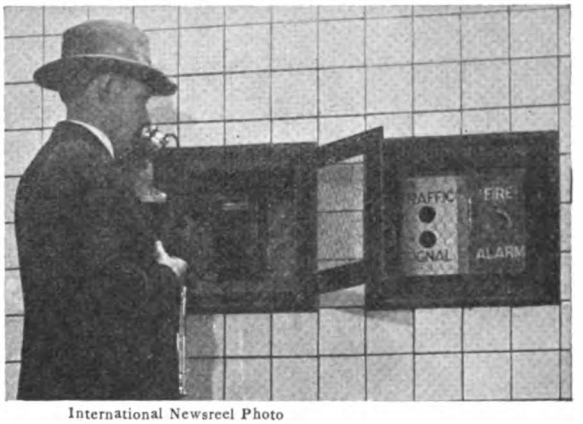


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FIG. 8—ONE OF THE TRAFFIC CONTROL STATIONS

and exhaust motor disconnecting switches (switches being closed), and the lower limit switch on the damper when the damper is closed. All these protective relays used with the motors operate a similar multi-contact relay, similar to one used on the incoming feeders, together with annunciator coils, the latter being used to indicate which fault tripped out the motor breaker.

### SUPERVISORY CONTROL

In addition to the two controls in the ventilation buildings, there is a third control, which is the supervisory or "master mind," located in the New York administration building. By means of transfer switches on the switchboards in all the ventilation, buildings, the control of all the feeders, transformers, and motor circuits can be transferred to the supervisory control board, which is operated by one man.

The control board, in the shape of an arc, Fig. 1, is a symbolic representation of both the twin tubes and the electrical circuits. It is divided by black vertical strips into five sections, representing the four ventilation buildings and the mid-river sump. The two large trough-like castings running horizontally, one near top and the other near the bottom of the control board, are likenesses as of the north and south tubes; the plateux at the ends represent the plazas with the arrow heads indicating the direction of traffic.

Every circuit breaker control switch, motor-speed switch, pump control switch, and their respective indicating lamps used in the tunnel equipment is duplicated on this board. By means of direct-wire connection through their respective relays, these various switches can control the various apparatus and the lamps will indicate accordingly.

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The large lamps located on the raised parts of the mimic tunnel, indicate what set of motors is feeding that particular section. The large lamp located in the trough is connected to the carbon monoxide recorder equipment. The illumination of this lamp indicates a high percentage of CO gas in the exhaust. The small lamps located in the line with the CO lamps, indicate the fire stations. The lights on the edge of the trough indicates what lighting cabinet is feeding the tunnel.

The supervisor can thus see how every piece of apparatus is performing: whether the incoming line circuit breaker is still feeding the equipment or else has tripped out automatically; whether the designated fans are running properly at the selected speed; and last, but not least, whether the percentage of poisonous gas is dangerous in any section of the tunnel and if a fire alarm has been sent in, what section is affects.

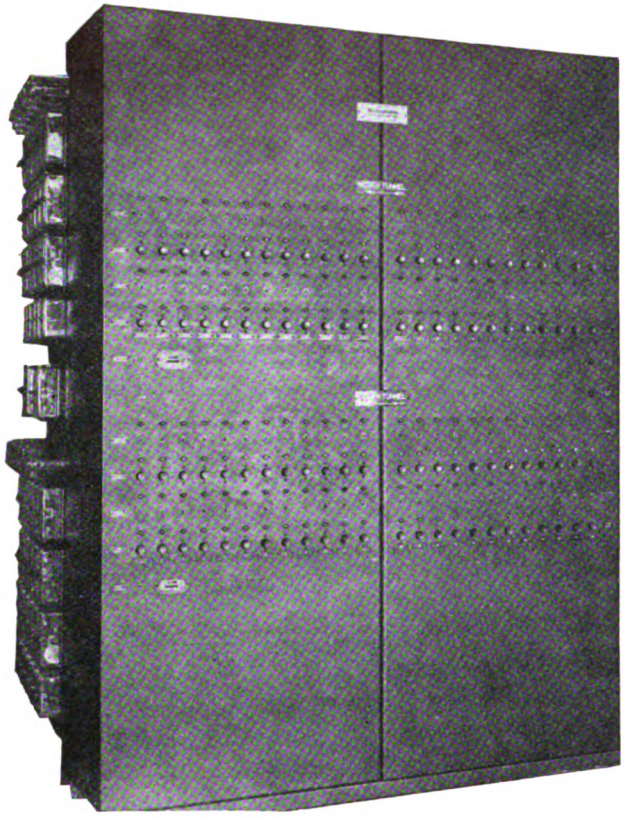

FIG. 9—FRONT VIEW OF THE TRAFFIC CONTROL BOARD

If, during the transfer period from switchboard to supervisory control, the portion of the various control and speed switches do not agree with what the switchboard has been, an alarm will be given until such switches are corrected. Such a feature always checks the functioning of the various apparatus.

In the same room, and to the right of the supervisory control board, stands the traffic signal board. The operation of this equipment, like the main control, can also be administered by the chief supervisor.

### TRAFFIC SIGNALS

Four kinds of signals are used to direct the motorists: green light indicates that the lanes are clear and traffic may proceed; red light indicates that traffic must stop; "stop engine" indicates that all engines must be stopped at once; yellow light indicates that all traffic must keep in the right-hand lane only.

The first three signals are in boxes as shown in Fig. 7, mounted near the ceiling on the left-hand wall of the tunnel above the walk-way. These signal light boxes are spaced 240 feet apart, while at every other box a traffic officer is stationed. Located at this point is the traffic light control buttons (go and stop), the fire alarm button and a telephone. Fig. 8 shows the traffic control station mounted on the wall of the tunnel.

Normally, only the green lights will be illuminated and the traffic is allowed to proceed. Should a traffic jam occur within the tunnel, the officer nearest the jam will press the *Stop* button, whereupon all traffic lights up to the point of trouble show red, thereby stopping incoming traffic. The lights beyond this point will stay green, permitting the traffic ahead to proceed. When the jam is cleared, the officer will change the red light to green by pressing the *Go* button.

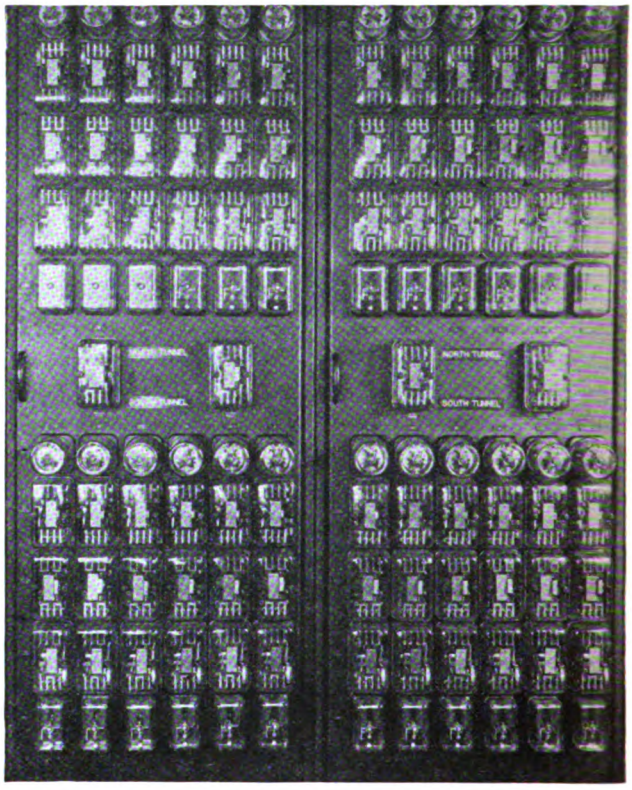

FIG. 10—REAR VIEW OF THE TRAFFIC CONTROL BOARD

Should a collision occur, the officer nearest the trouble will press the *Stop* button, thereby stopping incoming traffic. If the cars which collided require aid to remove them from the tunnel, the officer will call the chief supervisor by telephone. The operator will then notify the crew of the wrecking truck and at the same time will, by means of the traffic control board, illuminate the yellow lights from the exit of the tunnel to the point of accident. This latter signal will inform all officers between the accident and the tunnel exit that the emergency truck is coming in against traffic, and for them to instruct the outgoing traffic to keep to the

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right of the white line. After the wreck is removed the officer at the nearest station to where the accident occurred will change the red signal to green by pressing the *Go* button, and he will also notify the chief supervisor that the accident is cleared. The supervisor will then clear the yellow lights.

Should a fire occur from a collision, the officer nearest to the trouble will press the fire alarm button. The pressing of the fire-alarm button will change all signals behind the station to red, thus stopping incoming traffic, and will light all the yellow lights from the next station beyond, to the tunnel exist. At the same time a fire alarm is given at the traffic signal board and each one of the fire truck garages, where an annunciator indicates the station. The indication of the yellow light is the same in this case as when the trouble was a simple collision. At the sound of the alarm, the fire fighters, located at the exit of the tunnel in which the fire is present, will proceed into the tunnel.

As soon as the supervisory operator receives the fire alarm on the traffic board, he energizes the switch mounted alongside the *Stop Engine* sign. This will cause the *Stop Engine* signal to be illuminated in the tunnel wherever the red signal light is burning.

Between the traffic control buttons and the traffic sign and projecting out from the wall of the tunnel, is another box which has a yellow light at the top and a blue light at the bottom. The purpose of the yellow light has been explained above. The blue light indicates two things; first, when it blinks the traffic officer is to answer the telephone, in other words, it acts as a telephone bell; second, when the blue light is out, the control supply to that particular section of relays is open; thus the normal condition of the light is burning.

In the tunnel walls beside the traffic signal buttons, are cabinets wherein are mounted the relays, used for the traffic signals and telephones, and transfer relays used to transfer the voltage supply for the signals automatically from alternating to direct-current.

Working in conjunction with the tunnel signals and stations is the traffic signal board, located in the supervisory control room in the New York administration building. This board is composed of two steel cabinets, across the front of which are two tiers of lights and switches, the upper tier representing the signal stations for the north tunnel and the lower tier for the south tunnel. To each station there are four signal lights and four switches, as shown in Fig. 9. The upper row of lights, which have red lenses, operate in conjunction with the stop signals in the tunnel. The second row of lights, which have green lenses, are equivalent to the go signals in the tunnel. The third row of lights having yellow lenses, correspond to the yellow lights in the tunnel. The forth row, which have red lenses, are used to indicate the fire alarm stations. The lights behind the fire signal burn dim, normally and when a fire alarm station is operated by the policeman in the tunnel, the light opposite this station will burn brightly. By having two degrees of brilliancy on these lamps the operator can observe easily from which station the alarm was sent in.

The small switch between the red and green lights is for the operator's use. When thrown to the up position, it will operate all red signals from that station back to the entrance of the tunnel. When it is thrown to the up position, the officer in the tunnel cannot change the signals until the switch is turned to the down position. Should the supervisor wish to change the signals back to green, he first has to throw the small switch to the down position and then by pressing the push button below the green light, he will automatically re-set the signals back to green.

The small switch between the yellow and fire lights permits the operator to setup the yellow lights. By throwing this switch to the up position all yellow lights from this station to the exit of the tunnel will be illuminated. When a fire alarm is sent in from one particular station the red lights located on this board, from this station to the entrance of the tunnel, will be illuminated and the green lights extinguished for the same number of stations. The yellow lights, from the next station above to the exit of the tunnel will be illuminated. The supervisory operator is the only person who can re-set the fire alarm, and this is done by pressing the button opposite the station from which the alarm was sent. Re-setting the fire station will automatically cause the fire light at this station to return to the dim brilliancy and the yellow lights will be extinguished. The green, or go lights, will then have to be re-set by pressing the button located opposite to the station from which the fire alarm was sent in. Whenever a green signal is changed to red, either by the traffic officer or the supervisor, an alarm will be given; likewise, a klaxon will sound in case of fire. Fig. 10 shows a view of the relays used with 24 stations. The relays for the remaining stations are mounted on a swinging door within the cabinet.

### CARBON MONOXIDE RECORDER AND METERING EQUIPMENT

At the left of the main supervisory control board is another switchboard known as the CO and metering board. Upon this board are 14 graphic recorders, 7 for each tunnel, which record the amount of carbon monoxide in the exhaust gases. In addition to recording, this apparatus also sounds an alarm when the mixture of exhaust gases has over 3.5 parts of carbon monoxide in 10 000 parts of air, at the same time lighting the CO lamps located in the trough of the mimic tunnel on the main supervisory board. This board also has mounted upon its face two graphic recording wattmeters, one to indicate the total amount of power used from the New York feeders and the other to indicate the power used from the New Jersey feeders. These meters are operated by transmitters located in the respective land ventilation buildings.

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# Calculation of Sags in a Transmission Line with a Broken Conductor

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WHEN a transmission line crosses a railroad or a highway it is necessary to maintain a sufficient clearance between the level of the road and the overhead conductors. Often a definite clearance is specified, and in such cases it becomes of importance to know the sag of the span just above the road when a conductor breaks in one of the neighboring spans. The following method is given for calculating these sags.

A line of suspension insulators $AB$ is shown schematically in Fig. 1. The sags and tensions can be calculated by the usual methods, which have been described[1] fully and clearly. After the conductor has broken, the line will be in the condition shown in Fig. 2. Due to the difference in horizontal pull of the various conductors, the insulators will no longer be vertical, but will assume an angle of inclination $\alpha$, which is determined by the projections $h$ and $v$, as shown in Fig.

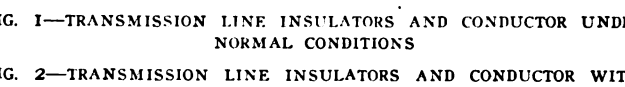


FIG. 1

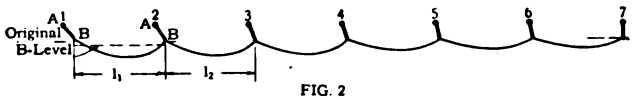


FIG. 2

FIG. 1—TRANSMISSION LINE INSULATORS AND CONDUCTOR UNDER NORMAL CONDITIONS

FIG. 2—TRANSMISSION LINE INSULATORS AND CONDUCTOR WITH A CONDUCTOR BROKEN

3. The spans are numbered so that number 1 is next to the break. The following notation is used:—

$l_1, l_2, l_3$ = horizontal distances between insulator end-points, in feet.
$h_1, h_2$ = horizontal projections of insulator, in feet.
$v_0$ = length of insulator, in feet.
$v_1, v_2$ = vertical projections of insulator, in feet.
$S_1, S_2$ = sags, measured from the original $B$ level of Fig. 1, in feet.
$H_1, H_2$ = horizontal pulls, in lbs.
$L_u$ = unstressed length of the span, i.e., the actual length of cable when not under tension.
$A$ = cross-section of cable, sq. in.
$M$ = modulus of elasticity in lbs. per sq. in. = $12 \times 10^6$.
$\beta$ = coefficient of linear expansion for copper per degree F. = $9.3 \times 10^{-6}$.
$i$ = total weight of insulator, in lbs.
$w$ = loading of cable per foot, in lbs.

After breakage, the ends of a span will no longer be on the same level. The effects of this on the pull $H$ are so small that they can be safely neglected. For the calculation of the pull in the cable, therefore, all points of suspension are assumed to be on the same level.

For the solution of the problem, two formulas are required. The first describes the equilibrium of a suspension insulator, and gives a relation between $H$, $v$ and $h$. The second gives a relation between the horizontal length $l$ of each span and the horizontal pull $H$.

In Fig. 3 all the forces acting on the $n$th insulator are shown. These are the two horizontal pulls $H_n$ and $H_{n-1}$, the vertical load $V$, which is equal to the weight of a full span of the cable, and the weight $i$ of the insulator itself. The insulator string remains sufficiently straight under these loadings to assume it to be without curvature.

For equilibrium the moment about $A$ must be zero, or:—

$$(H_n - H_{n-1})\, v_n = (V + i/2)\, h_n \quad \ldots\ldots (1)$$

For the first insulator, $V$ is not equal to the weight of a full span, but rather to one-half this weight, plus the weight of the broken wire hanging from it.

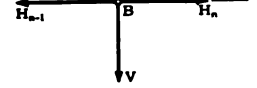


FIG. 3—FORCES ACTING ON THE NTH INSULATOR

The second formula is derived from the well-known formulas[2] of the parabola.

The sag is,—

$$S = \frac{w l^2}{8 H} \quad \ldots\ldots (a)$$

The length of cable is,—

$$L = l + \frac{8 S^2}{3 l} = l + \frac{w^2 l^3}{24 H^2} \quad \ldots\ldots (b)$$

This length $L$ is the actual length of the line. The unstressed length $L_u$ is shorter.

$$L = L_u \left(1 + \frac{H}{A M}\right) \quad \ldots\ldots (c)$$

Equating these two values for $L$ gives:—

$$\frac{L_u}{A M} H^3 + (L_u - l)\, H^2 - \frac{w^2 l^3}{24} = 0 \quad \ldots\ldots (2)$$

which is the required relation between $H$ and $l$.

A direct solution of this problem is not possible. However, by a method of trial and error the true solution can be approached within any desired limit. The procedure is as follows:—Assume some value for $H_1$, the pull in the first span. About 60 percent of the pull in the unbroken line is a good first guess. Substitute

[1] In a series of articles on "Mechanical Characteristics of Transmission Lines" by L. E. Imlay in the JOURNAL in 1925.

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this value in eq. (1) and calculate $h_1$ and $v_1$. Also substitute $H_1$ in eq. (2) and calculate $l_1$. With these values of $l_1$ and $h_1$, it is easy to find $h_2$. Substituting $h_2$ in eq. (1) gives $H_2$. Substitute this in eq. (2), etc.

By successive substitution in eqs. (1) and (2) the values of $h$, $v$ and $H$ are calculated for several spans. Soon it is possible to discern whether the first choice for $H_1$ has been too large or too small. If $H_1$ were chosen just right, the inclination of the consecutive insulators would become less and less, and insulators at a great distance from the break would be vertical, as shown in Fig. 2. If $H_1$ is chosen too small the inclinations $\alpha$ become smaller more rapidly than in the previous case. The insulators finally go through the vertical position and become inclined in the other direction, as in Fig. 4. In case $H_1$ had been assumed too large, the rate of decrease of the inclinations would be too slow. The angle of inclination would reach a minimum, and then would increase again, as in Fig. 5. No one insulator would ever be truly vertical.

After it is recognized that the first choice for $H_1$ has been too small or too large, the calculation is repeated with another value of $H_1$. That number of insulators where the minimum inclination $\alpha$ is reached in case of too large $H$, or where the insulator goes

TABLE I-RESULTS OF FIRST TRIAL CALCULATIONS

| $n$ | $K_n v_n$ | $h_n$ | $H_n$ | $l_n$ |
|---|---|---|---|---|
| 1 | 0.57 | 3.95 | 1500 | 598.59 |
| 2 | 3.09 | 2.54 | 1839 | 599.25 |
| 3 | 3.58 | 1.78 | 2044 | 599.52 |
| 4 | 3.78 | 1.30 | 2186 | 599.67 |
| 5 | 3.88 | 0.97 | 2289 | 599.77 |
| 6 | 3.93 | 0.74 | 2366 | 599.84 |
| 7 | 3.95 | 0.58 | 2426 | 599.90 |
| 8 | 3.96 | 0.48 | 2476 | 599.94 |
| 9 | 3.98 | 0.415 | 2519 | 599.98 |
| 10 | 3.98 | 0.395 | 2560 | 600.00 |
| 11 | 3.98 | 0 395 | 2601 | 600.03 |
| 12 | | 0.422 | | |

through its vertical position in case of too small $H$ will be designated as the critical number. This critical number is an indication of the accuracy of the guess; the larger the critical number the nearer the assumed value is to the correct value for $H_1$. After having made two calculations for different values of $H_1$, the two critical numbers thus obtained may be used for interpolating or extrapolating a third value for $H_1$. This will be illustrated in an example.

## NUMERICAL EXAMPLE

For a certain transmission line the distance between towers is 600 feet, the conductor is 4/0 stranded copper cable. The insulators weigh 50 pounds each and are 4 feet long. It is further given that under Class B loading[2] and at zero degrees F. the horizontal pull $H$ = 5000 pounds. It is desired to determine the sags at a temperature of 60 degrees F. after a conductor has broken. It has been calculated[2] that the length of the parabola at zero° F under Class B loading is 600.97 feet; the unbroken sag is 14.78 feet. The cross-section of the cable is $A$ = 0.166 sq. in. The unstressed length at zero degree F. then becomes, by formula (c):—

$$L_u = 600.97\left[\frac{12\times10^6\times0.166}{5000+(12\times10^6\times0.166)}\right] = 599.46 \text{ feet.}$$

At 60 degrees F. it becomes:—

$$L_u = 599.46\ (1+60\beta) = 599.80 \text{ feet.}$$

This is the value for $L_u$, which has to be substituted in eq. (2) in order to solve the problem for a temperature of 60 degrees F. The weight of this cable is $w$ = 0.645 lbs. per ft. The vertical pull $V$ at any insulator except the first is $600\ w$ = 387 pounds. If the conductor breaks just next the first insulator, its vertical pull becomes 387/2 = 193.5 pounds.

FIG. 4

FIG. 5

FIG. 4—CASE OF TOO SMALL AN ASSUMPTION FOR $H_1$

FIG. 5—CASE OF TOO LARGE AN ASSUMPTION FOR $H_1$

With the values given above eq. (2) becomes, for this problem:—

$$0.0003H^3 + (599.80 - l)\ H^2 = 0.0173\ l^3$$

The approximate value of $l$ = 600 feet may be substituted in the right-hand member of the above equation without introducing a material error. It then becomes:—

$$l - 599.80 = 0.0003\,H - \frac{3\,740\,000}{H^2} \quad \ldots\ldots\ldots\ldots (3)$$

With this formula the stress in the unbroken line under dead load at 60 degrees F. will be calculated. Then $l$ = 600 feet and solving eq. (3) H is found to equal 2565 pounds.

TABLE II-RESULTS OF SECOND TRIAL CALCULATIONS

| $n$ | $K_n v_n$ | $h_n$ | $H_n$ | $l_n$ |
|---|---|---|---|---|
| 1 | 0 58 | 3 92 | 1480 | 598 53 |
| 2 | 3 16 | 2 45 | 1800 | 599 19 |
| 3 | 3 74 | 1 64 | 1980 | 599 44 |
| 4 | 3 85 | 1 08 | 2096 | 599 58 |
| 5 | 3 94 | 0 66 | 2165 | 599 65 |
| 6 | 3 99 | 0 31 | 2197 | 599 68 |
| 7 | 4 00 | 0 | 2197 | 599 68 |
| 8 | 3 99 | 0.32 | 2165 | |

TABLE III—SAG WITH A BROKEN CONDUCTOR AT 60° F.

| Span | $H$ | $l$ | Sag Ft. | Sag below Original B-Level—Ft. |
|---|---|---|---|---|
| 1 | 1490 | 598 56 | 19 4 | 17 3 |
| 2 | 1820 | 599 22 | 15 9 | 15 3 |
| 3 | 2012 | 599 48 | 14 4 | 14.2 |
| 4 | 2141 | 599 62 | 13 5 | 13 4 |
| 5 | 2227 | 599.71 | 13 05 | 13.0 |

After fracture of the line, the stress in the first span will be smaller than this. As a first guess take roughly 60 percent; $H_1$ = 1500 pounds. From eq. (1) we calculate:—

$$1500\ v_1 = 218.5\ h_1$$
$$h_1^2 + v_1^2 = v_0^2 = 16$$

therefore:—

$$h_1 = 3.95 \text{ feet} \qquad v_1 = 0.57 \text{ feet}$$

From eq. (3) with $H_1$ = 1500, we find $l_1$ = 598.59 feet. Then:—

$$h_1 - h_2 = 600 - l_1$$

whence: $h_2 = 2.54$ feet $\quad v_2 = \sqrt{16 - h_2^2} = 3.09$ feet

[2]Given in the JOURNAL for February 1925, p. 53.

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Substituting in eq. (1):—

$3.09\ (H_2 - 1500) = 412 \times 2.54$ or $H_2 = 1839$ pounds.

Extending the calculation in this manner the results given in Table I are obtained. It is seen that $h$ reaches its minimum of 0.395 feet at the tenth insulator. Therefore $H_1 = 1500$ is too large. The fact that the critical number is 10 indicates that 1500 is very near to the actual value. As a second guess take $H_1 = 1480$ pounds. This calculation leads to the values given in Table II.

The calculations show that $H_1 = 1480$ is too small. The seventh insulator is exactly vertical; hence the critical number is seven. The range of critical values is 10 (high) to 7 (low) or a total of 17. Therefore the next value* to try for $H_1$ is:—

$$1480 + \left(\frac{10}{17} \times 20\right) = 1492$$

However the result already obtained is sufficiently accurate for most purposes.

For calculating the sags, by means of formula (a) the averages of the values for $H$ and $l$ in the two tables are taken. This gives the sags with respect to the actual end points of the span. In order to find the sags with respect to the original B-level, the value $v_0 - \frac{v_n + v_{n+1}}{2}$ must be subtracted from $S_n$. This gives the final result shown in Table III. For comparison it is calculated that the sag in a vertical plane of the unbroken line is:—

Sag at 0 degrees F., Class B loading .....11.4 feet
Sag at 60 degrees F., dead weight only .....11.3 feet

*Suppose the critical values had been 4 (high) for 1500, and 10 (high) for 1480. The next number to try would have been $1480 - \left(\frac{4}{14} \times 20\right)$.

# The Work of Oliver Heaviside

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THERE is a reference in that beautiful book of Lord Rayleigh's on "The Theory of Sound"[1], on the subject of electrical vibrations to which we may devote a few moments consideration. Lord Rayleigh says: "The theory of electric currents in such wires as are commonly employed in laboratory experiments is simple, mainly in consequence of the subordination of electrostatic capacity. When this element can be neglected, the current is necessarily the same at all points along the length of the wire, so that *whatever enters a wire at the sending end, leaves it unimpaired at the receiving end.* In this case the whole electrical character of the wire can be expressed by two quantities —its resistance $R$ and inductance $L$—and *these may usually be treated as constants*, independent of the frequency." For clearness the vital part of the statement is given in italics.

To introduce the reader further into the subject in which the genius of Heaviside has blazed a path of singular clarity and beauty, we shall follow Lord Rayleigh further in his simple presentation rendered in 1894. "Circuits employed for practical telephony may often be regarded as coming under the above description, especially when the wires are suspended and are of but moderate length. But there are other cases in which electrostatic capacity is the dominating feature. The theory of electric cables was established many years ago by Lord Kelvin[2] for telegraphic purposes." A simple review of the mathematical argument will help to refresh the memory, and it is very simply given by Rayleigh. Thus we shall continue: "If $S$ be the capacity and $R$ the resistance of the cable, reckoned per unit length, $V$ and $C$ the potential and the current at the point $z$, we have,—

$$S\frac{dV}{dt} = -\frac{dC}{dz}, \quad RC = -\frac{dV}{dz} \ldots\ldots (1)$$

whence

$$RS\frac{dC}{dt} = \frac{d^2C}{dz^2} \ldots\ldots (2),$$

the well known equation for the conduction of heat discussed by Fourier."

Let us digress for the moment from Lord Rayleigh's exposition and dwell on the fact that Kelvin's entire cable theory was built up on the conception of "electric diffusion", rather than on a theory of propagation of waves along conductors. Electric waves were, of course, not thought of at the time William Thomson formulated his theory of the electric telegraph, and it is natural enough that he followed Fourier in establishing a partial differential equation for the diffusion of electricity through a cable, an equation the solution of which was rendered possible through Fourier's epoch-making work beginning in 1807, and ending in 1822. Thus there was a period of only thirty-three years between Thomson's paper and the mathematical theory which made that paper possible. This is instructive in comparing the development in regard to the mathematical work of Heaviside and its application to engineering problems.

We now continue with the very direct solution of the Fourier partial differential equation (2), assum-

[1] "The Theory of Sound", By John William Strutt, Baron Rayleigh. Vol. I, p. 466 et seq. London: Macmillan Co., 1894.

[2] The date of Lord Kelvin's paper on "The Theory of the Electric Telegraph" is May, 1855. The paper written when he was plain Professor William Thomson and before a workable transatlantic cable connected this country with Ireland, is well worth careful study even in this day. It is reprinted in Vol. II, p. 61, of "Mathematical and Physical Papers", Cambridge, 1884. Lord Kelvin limited himself strictly to distributed resistance and capacity neglecting inductance.

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ing the variation of the current, here denoted with $C$ following the earlier custom of the time, to be sinusoidal, expressed operationally by $C = C_0 \epsilon^{ipt}$, where $\epsilon$ is the Naperian base of logarithms, $p = 2\pi/T$ the angular velocity of the current, $T$ the time of a complete period, $p/2\pi$ the frequency, $t$ the time, and $i = \sqrt{-1}$, now frequently designated by $j$. "On the assumption that $C$ is proportional to $\epsilon^{ipt}$, it reduces to,—

$$\frac{d^2C}{dz^2} = \left\{\sqrt{\left(\frac{1}{2}\ p\,R\,S\right)}\left(1+i\right)\right\}^2 C \quad \ldots\ldots (3)$$

so that the solution for waves propagated in the positive direction is,—

$$C = C_0\,\epsilon^{-\sqrt{\frac{1}{2}pRS}\cdot z}\cos\left(pt - \sqrt{\left(\frac{1}{2}\,p\,RS\right)}\cdot z\right) \ldots (4)$$

The distance over which the current is attenuated in the ratio of $\epsilon$ to 1 is thus,—

$$z = \sqrt{\frac{2}{p\,R\,S}} \quad \ldots\ldots (5)$$

"A very slight consideration of the magnitudes involved is sufficient to give an idea of the difficulty of telephoning through a long cable. If, for example, the frequency ($p/2\pi$) be that of a note rather more than an octave above middle $c$, and the cable be such as are used to cross the Atlantic, we have in C. G. S. measure,—

$$\sqrt{p} = 60,\ (R\,S)^{-1} = 2 \times 10^{16},$$

and accordingly, from (5),—

$z = 3 \times 10^8$ *cm.* = 20 miles approximately.

"A distance of 20 miles would thus reduce the intensity of sound, measured by the square of the amplitude, to about a tenth, an operation which could not be repeated often without rendering it inaudible. With such a cable the practical limit would not be likely to exceed fifty miles, more especially as the easy intelligibility of speech requires the presence of tones still higher than is supposed in the above numerical example.

"In the above theory the insulation is supposed to be perfect and the inductance to be negligible. It is probable that these conditions are sufficiently satisfied in the case of a cable, but in other telephonic lines the inductance is a feature of great importance. The problem has been treated with full generality by Heaviside....." Then Lord Rayleigh refers his readers to Vol. II of Oliver Heaviside's "Electrical Papers", pp. 125 and 309, reprinted from *"The Electrician"*, London, 1886-7.

The limitations to long distance telephony had been recognized and analyzed with great skill and acumen by Thomas H. Blakesley, of the Royal Naval College, Greenwich, in a series of papers[3] published in *"The Electrician"*, October, 1885. This remarkable series of papers treated the problems of series and parallel connection of resistances, inductances, and capacity from the point of view of the modern vector methods. Distributed capacity and inductance are also treated, and most useful hyperbolic tables are given for the calculation of phenomena with distributed constants. Prof. Blakesley introduced his papers with a preface from which it is instructive to quote to bring out a useful sidelight on the general status of knowledge in the year 1885. "I have elsewhere strongly disapproved of the action of the Board of Trade", says Professor Blakesley, "in allowing electricity in alternating currents to be distributed on a large scale publicly. Nor must I be held recommending this in the following chapters. But in the last one I have shown how harmonic currents may be advantageously used for measuring some of the electric properties of a circuit, and consequently as a means of testing be found extremely useful." He would thus forbid the use of alternating currents. This extraordinary statement gives a good idea of the difficulties of the early pioneers who, like Tesla and Kapp, like Ferranti and Mordey, were about to begin their labors in applying alternating currents to the distribution of power.

Blakesley gives another helpful conception when, on p. 63 of the papers already cited, he says of the state of the art of telephony: "Thus at the end of any considerable length and capacity the various tones of the voice would be received in a state of degradation depending upon their pitch. But the ear has not the synthetic power of reconstructing a composite tone from the wreck of variously degraded components. In this consideration lie the limits of telephony. And until it is more clearly understood than it seems to be at present, people will fail to understand the exquisite nonsense to which they are often now content to listen."

Thus it required the treatment by Oliver Heaviside of the propagation of electric impulses along wires "with full generality"—to use Lord Rayleigh's happy phrase—to clarify the intricate problems involved in the transmission of speech and power over a long line with the characteristic constants of resistance, inductance, capacitance, and leakance. This work was done in masterly fashion, and its development took place in opposition to the prevailing ideas of the time which, following the methods used in ocean telegraphy, laid great stress upon the electrostatic capacity of the cable and condemned as injurious both the inductance and the leakance of the circuit. As Lord Rayleigh says, "It might perhaps have been expected that a finite leakage would always act as a complication; but Heaviside has shown that it may be so adjusted as to simplify the matter."[4]

These introductory remarks are made to acquaint the reader with the nature of the problem, the discussion of which forms the principal work of Heaviside and, therefore, the substance of this article.

[3] "Alternating Currents of Electricity", by Thomas H. Blakesley, London: Published at the office of *"The Electrician"*, 1 Salisbury Court, Fleet Street, E. C., 1885.

[4] Oliver Heaviside, *"Electrician"* June 17, 1887. "Electrical Papers", Vol. II pp. 125, 309. Also his simple and beautiful treatment of the distortionless circuit in "Electromagnetic Theory" vol. I, pp. 409, 419, 1893 and Vol. II, pp. 291, 1899. The last reference was not available to Lord Rayleigh at the time, 1894, when his "Theory of Sound" was published.

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### THE HISTORICAL SETTING

The electric transmission of speech is a process of power transmission. To be sure the amount of power is small though, metaphorically, the power of speech is great. But though only a small amount of power is transmitted in telephony over a great distance, the process of transmission and the theory thereof are truly identical. Great emphasis should be laid on this statement, and the reader should challenge its truth so as to convince himself that these two processes, seemingly so different, are, in truth, identical.

Thus if the theory of the electric cable is once obtained with "full generality", this theory must explain, not merely the vast branch of phenomena of telephony and telegraphy, but also the equally vast field of the problems involved in the transmission of power.

Power transmission and speech transmission hold the stage of discussion on the broadest scale at the moment. Can a time be more suitable, forty years after the presentation of such a theory, for a review of the work of its foremost protagonist?

### THE SETTING OF THE STAGE

I am going to take the reader to the year 1887, and set before him in broad outline the condition of electrical engineering at that time. Power engineering and telegraph and telephone engineering had not yet been separated. The American Institute of Electrical Engineers was barely three years old. Maxwell's electromagnetic theory based on Faraday's experimental researches, eliminating the conception of action at a distance, had led him to the prediction of the existence of electromagnetic waves in space propagated with the velocity of light and akin to light except for their greater wave length. The existence of these waves was brilliantly demonstrated by Hertz through his discovery, in 1887, of electromagnetic waves in space and along wires showing all the characteristics of refraction and reflection, only on an infinitely larger scale than light waves. Oliver Lodge had also demonstrated electric waves along wires. These are the waves we are now all familiar with as the waves used in radio-telegraphy and broadcasting.

It is not often in the history of science that so stirring a discovery is made as that of electromagnetic waves predicted in all their characteristics long before their discovery. One has to go back to the finding in its calculated place of the unknown planet Neptune, whose existence and position were predicted in 1846 by Leverrier and Adams, to be found shortly afterward in the predicted place by Prof. Galle. Here the discovery followed quickly on the prediction, whereas it took twenty years for the electromagnetic waves to make their appearance after their prediction.

Power transmission was attempted by all means except by electrical means, the exception proving the rule. A little plant of fifty horsepower in Switzerland, operating at 2000 volts direct current, transmitted this power over a distance of five miles. This plant was designed by C. E. L. Brown. Nikola Tesla had not yet made his great inventions. The telephone, invented simultaneously by Alexander Graham Bell and Elisha Gray in 1876, was hardly a decade old.

This is a bare outline of the condition of the electrical field at the time when, in 1887, we become acquainted with Oliver Heaviside.

### A PERSONAL SKETCH

The biographical data which are obtainable regarding Heaviside are meager and besides, to a great extent, are of a very personal and, therefore, of a private nature. Born in London on May 13, 1850, Oliver Heaviside died in complete seclusion on February 3, 1925. The last fifty years of his life were spent in this retirement, the greater part at Torquay on the south coast of Devonshire. He was a nephew of Sir Charles Wheatstone, who is known as the father of telegraphy, the inventor of the "Wheatstone" bridge and of the principle of self-excitation of the dynamo-electric machine. Doubtless Heaviside inherited the gift of physical interpretation from the Wheatstone, on his mother's side. Heaviside's means were very limited, in fact he died in what would be to most of us a state of poverty. It seemed to the present writer that he lacked the necessary care which a man of his age, not to mention his greatness as a mathematical physicist, should have had. It was, however, difficult to render assistance of any kind as he was a proud man and deeply sensitive. He received a small pension from the British government, which was augmented by an annuity from the British Institution of Electrical Engineers. The writer has given elsewhere a sketch of Heaviside's life.[5]

During the last ten years of his life Heaviside received numerous proofs of the great respect in which he was held by those who see in the intellectual progress of mankind the principal hope for the future. In 1918, he received one of the two honorary memberships of the American Institute of Electrical Engineers, which usually go to British men of science or engineering. In 1921, he received the first Faraday Medal of the Institution of Electrical Engineers of Great Britain, and the president of the Institution himself journeyed to Heaviside's lonesome country place to present the medal to "one whose genius, perspicacity, and clearsightedness into fundamentals entitle him to be ranked with the greatest of philosophers, Archimedes, Newton, Kelvin and Faraday." Whether these eulogistic terms are extravagant—the British are not apt to use superlatives—must be left to the judgment of future generations.

It is, however, pleasant to those of us who were his friends to know that, before he passed away, his work was appreciated on all hands and there was no voice bold enough to deny the greatness and inspiration of this wonderful mind. Well might one have ex-

[5] *Electrical World*, February 21, 1925. Memorial Sketches of Oliver Heaviside by Sir Oliver Lodge and B. A. Behrend.

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claimed on the news of his death, "Let there be silence in the telephone, for Oliver Heaviside has died!"

ELECTROMAGNECTIC INDUCTION AND ITS PROPAGATION

To the engineer it is natural that the subject of the propagation of electromagnetic induction offers the most fruitful field of inquiry. This subject may, therefore, be examined and a brief analysis, following Heaviside, be given.

In 1887, Heaviside started his series of papers in the *"Electrician"* on electromagnetic waves.[6] It must be remembered that at the time these papers were written no such waves had been observed, but the prediction which was made by Maxwell was, of course, known to his principal interpreter. Before Hertz discovered Maxwell's waves, Heaviside writes equally prophetically: "When we have little distortion, we get into the region of radiation. The dielectric should be the central object of attention, the wires subsidiary, determining the rate of attenuation. The waves are waves of light, in all save wave-length, which is great, and gradual attenuation as they travel, by dissipation of energy in the wires. There is the electric disturbance and the magnetic disturbance keeping time with it, and perpendicular to it, and both perpendicular to the transfer of energy, which is parallel to the wire, very nearly. A tube of energy current may be regarded as a ray of light (invisible, of course).

"It is to such *long* waves that I attribute the magnetic disturbances that come from the sun occasionally, and simultaneously show themselves all over the world; arising from violent motions of large quantities of matter, giving shocks to the ether and causing passage from the sun of waves of enormous length. On such a wave passing the earth, there are immediately induced currents in the sea, earth's crust, telegraph lines, etc."[7] Such reasoning is to us perfectly familiar, but it was Heaviside who made it familiar to us.[8] We shall have occasion frequently to direct the reader's attention to the valuable comments and to the work of such eminent physicists as Lorentz in its bearing on, and connection with, the work of Heaviside. His long struggle for recognition was rewarded a few years before his death by a careful and profound study of his work, not only by the few who had previously gleaned valuable information from it, but also from the orthodox school of eminent men of science. It was fortunate that he lived to see his work thus forming the foundation of electrical knowledge, though he had no share in the great material prosperity which it had wrought for the world.

The problem which occupied Heaviside in the middle eighties was then primarily the propagation of electromagnetic force in space and along parallel conductors. The former led him to formulate the fundamental equations of electromagnetic theory in the form of a symmetrical pair of the electric and magnetic forces. These are the circuital equations of Maxwell in their simplified vectorial form, and which Heaviside writes,—

$$\text{curl } \mathbf{H} = \mathbf{J}$$
$$-\text{curl } \mathbf{E} = \mathbf{G}$$

The latter led to the "telephone equation" which I shall discuss at greater length. I propose to take the reader to Heaviside's paper in which he discusses the method of approach which he followed forty years ago, and which led him to the discovery of the "distortionless circuit" and to the theory of long cables and lines for the transmission of alternating currents.

It is well-known how unmanageable the solutions of differential equations appear when general functions are used as solutions. Heaviside recognized this. "In some respects", he says, "these difficulties are evaded by the consideration of the solution due to a sinusoidal impressed force. The method is very powerful; and, by considering the nature of the result through a sufficiently wide range of frequencies, we may indirectly gain, with comparatively little trouble, knowledge that is unattainable by the method of normal systems."

"But the real desideratum which, if it can be reached, is of paramount importance, is to get solutions which can be understood and appreciated at first sight, and followed into detail with ease, presenting to us, as nearly as possible, the effects as they really occur in the physical problem, disconnected from the often unavoidable complications due to the form of mathematical expression. To illustrate this, it is sufficient to refer to the elementary theory of the transmission of waves without dissipation along a stretched flexible cord. If we employ Fourier-series, we are doing mathematical exercises. But, use the other method, in which arbitrary disturbances are transferred bodily in either direction at constant speed, e.g.,—

$$u = f(z - vt),$$

and we ge rid of the mathematical complications, and can interpret results as we see their physical representatives in reality—for instance, when we agitate one end of a long cord.

"Now there is one case, and, so far as I know at present, only one, in the many-sided question of the transmission of electromagnetic disturbances along wires, which admits of this simple and straightforward method of treatment. Singularly enough, it is not by the simplifying process of equating to zero certain constants, and so ignoring certain effects, that we reach this unique state of things, but rather the other way, generalizing to some extent. It is usual to ignore the leakage of conductors, sometimes also the inductance, and sometimes the permittance (permittance is the term used by Heaviside for what he called later capacitance).

[6] "Electrical Papers", Vol. II, p. 39, "Electromagnetic Induction and its Propagation" (Second Half) London, Macmillan Company, 1892. The first half appeared in 1885 and following and it is published in the first volume of the "Collected Papers". It deals principally with Maxwell's theory.

[7] "Electrical Papers", ibid. Vol. II, p. 122.

[8] "That we have got so far is due in the first place to Maxwell, and next to him to Heaviside and Hertz." Problems of Modern Physics, by H. A. Lorentz. A Course of Lectures delivered at the Calif. Inst. of Tech. Published by Ginn & Co., Boston, 1926, p. 5.

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But we must take all the four properties into account which are symbolized by resistance, leakage-conductance, inductance and permittance, to reach the much-desired result. Briefly stated, the effects are these, roughly speaking: If there be only resistance and permittance, there is, when disturbances of an irregular character are sent along a long circuit, both very great attenuation and very great distortion produced. The distortion at the end of an Atlantic cable is enormous. Now if we introduce leakage, we shall lessen the distortion considerably, but at the same time increase the attenuation. On the other hand, if we introduce inductance (instead of leakage) we shall lessen the attenuation as well as the distortion. And, finally, if we have both leakage and inductance, in addition to resistance and permittance (capacitance) we may so adjust matters, by the effects of inductance and of leakage, being opposite as regards distortion, as to annihilate distortion altogether, leaving only attenuation. The solutions can now be followed into detail in various cases without any laborious and roundabout calculations. Besides this, they cast much light upon the more difficult problems which occur when not so many physical actions are in question.

"In my usual notation, let $R$, $L$, $S$ and $K$ be the resistance, inductance, permittance and leakage-conductance of a circuit, per unit length, all to be treated, in the present theory, as constants; and let $E$ and $I$[9] be the transverse voltage (this term was also first used by Heaviside) and the current at distance $z$. The fundamental equations are,—

$$-\frac{dE}{dz} = (R + Lp)\, I, \quad -\frac{dI}{dz} = (K + Sp)\, E,$$

$p$ standing for $d/dt$. Here $I$ is related to the space-variation of $E$ in the same formal manner as $E$ to the space-variation of $I$. This property allows us to translate solutions in an obvious manner, and gives rise to the distortionless state of things. Let,—

$$L\,S\,v^2 = 1, \text{ and } R/L = K/S = q$$

The equation of $E$ is then,—

$$v^2 \frac{d^2E}{dz^2} = (q + p)^2\, E$$

and the complete solution consists of waves travelling at speed $v$ with attenuation but without distortion. Thus, if the wave be positive, or travel in the direction of increasing $z$, we shall have, if $f_1(z)$ be the state of $E$ initially,—

$$E_1 = \epsilon^{-qt} f_1(z - vt)$$
$$I_1 = E_1/Lv$$

"If $E_2$, $I_2$ be a negative wave, travelling the other way,—

$$E_2 = \epsilon^{-qt} f_1(z + vt)$$
$$I_2 = -E_2/Lv$$*

It is now advisable to refer to "Electromagnetic Theory", Vol. I, p. 451, 1893, where Heaviside gives the solution of his general equation in the form which has proved best adapted to the purposes of electrical engineering. The equation is familiar to all who are acquainted with power transmission problems. The electromotive force necessary to maintain, at the end of a line whose length is $x$, a current $I_0$ and a voltage $E_0$ is,—

$$E = E_0 \times \cosh qx + I_0 \times Z_0 \frac{\sinh qx}{q} \quad \ldots\ldots (10)$$

In this equation, which is the fundamental general solution,—

$$q = \sqrt{(r + jL\omega)\,(g + jC\omega)}$$
$$= \sqrt{ZY}$$
$$Z_0 = \sqrt{Z/Y}$$

Hence, the Heaviside equation (10) can be written,—

$$E = E_0 \cosh qx + I_0 Z_0 \sinh qx \quad \ldots\ldots (11)$$

In this form the equation retains the character of the simple application of Ohm's law by introducing the "surge impedance" which Heaviside—without using the name which was given it later by Professor Kennelly—first introduced to us in "Electrical Papers", Vol. II, p. 369, equation (38), 1887.

To those who have made calculations of long lines, equation (11) is familiar. It is easy to remember, and equally easy to see its connection with the nature of the power transmission problem. The generator voltage equals the receiver voltage plus the drop of potential in the line, exactly as it would be in a direct-current circuit, but both the receiver voltage and the line drop appear multiplied by a function which is a directional quantity or a vector or a complex quantity. This is, of course, obviously necessary by inspection, as the receiver voltage and the line drop must have direction as well as magnitude when dealing with alternating-current circuits.

It is customary to speak of "hyperbolic functions" and their applications to electrical engineering problems[10]. It is, perhaps, a little unfortunate that such names inject a little fear and apprehension into the reader as he feels that something new and difficult is about to be practiced on him. These functions are simply a convenient grouping of operators of the same nature as the complex quantities which are, after all is said and done, solely a kind of convenient shorthand to reduce labor and make the clerical part of it less cumbersome.

### THE DISTORTIONLESS CIRCUIT

We were concerned particularly with the conception of the distortionless circuit and its meaning in connection with alternating-current power transmission or speech transmission. It is not easy to follow Heaviside,

[9]Heaviside uses $V$ and $C$ for voltage and current but I have deemed it wise to use the notations to which we are more accustomed in order to show the obvious identity between our modern equations and the historical ones of Heaviside's.

*"Electrical Papers", Vol. II, p. 308 et seq.

[10]A. E. Kennelly, "Hyperbolic Functions and their Applications to Electrical Engineering Problems", Second Edition, London: University of London Press, Ltd., 1917; "Artificial Electric Lines", McGraw-Hill Book Co., New York, 1917; William Nesbit, "Electrical Characteristics of Transmission Circuits", 3rd Edition, 1926.

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although intensive study enables one to fall into his mode of working out his problems. It must be remembered that here was a problem baffling the ablest mathematicians, physicists and engineers and that a novel form of approach had to be designed before the problem would yield to analysis. I will choose here a different way, radically different from Heaviside's, though it received the stamp of his approval. It is a method suitable to the mode of thought of the engineer and its great simplicity and directness parallel the method used by Heaviside to work out his solution.

Heaviside proceeds from the thought that it is necessary, if long distance telephony is to be made practicable, that the "guides" of the electric propagation, in other words the line, must have such constants that impulses of all frequencies are propagated at the same speed along these "guides" and are attenuated alike in transmission. Now, as our quotations from his papers indicate, he felt that it would be easier to obtain this condition while working with four line constants than it would be if he had to work with the two constants

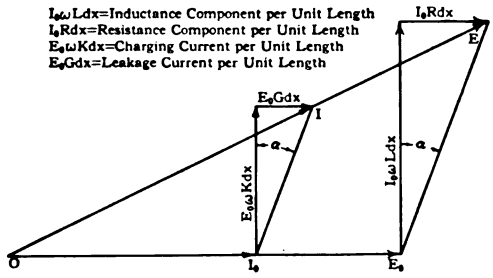


FIG. 1—VECTOR DIAGRAM FOR TRANSMISSION LINE, CURRENTS AND VOLTAGES BEING IN PHASE

used in telegraphy by Lord Kelvin, the resistance and the condensance only. That he solved the distortionless problem before he solved the general problem is instructive.

The object, then, is to obtain waves without alteration of type. Such waves may be attenuated, that is, reduced in geometric proportion, weakening the strength of the signal, but they must not be distorted, that is, part of a wave consisting of a certain frequency must not arrive "out of place" with other parts consisting of another frequency.

In language more familiar to us the statement can be made as follows: the e.m.f. and the current must retain the phase relation which they have at the sending end. Change in phase relation is distortion. I shall now formulate the problem as follows: To design a circuit through which alternating currents can be transmitted in such a manner that the e.m.f. and the current remain in time phase and attenuating alike, independent of the frequency.

Starting at the receiving end, we assume the e.m.f. and the current of the receiving apparatus to be in phase. Any other relation can be worked out in the same way. Let $R$ be the resistance per unit length, $G$ the leakage conductance, $L$ the inductance, and $K$ the capacitance, all per unit length of the circuit. Now let us build up the voltage and the current from the receiving end in the usual manner by means of e.m.f. and current vectors keeping, however, before us the condition that the current and the e.m.f. must remain in time phase. This condition will be realized, as is shown at a glance, so long as the e.m.f. and current vectors remain always in time phase, which means that the current and e.m.f. triangles must be similar. This condition prevails, as shown in Fig. 1, when $R/G = L/K = \tan \alpha =$ a constant. But this is no other than the Heaviside criterion.

But let us go a step farther and interpret Heaviside's solution (10) for this particular case. The differential equation which is the fundamental starting point is,—

$$\frac{d^2 E}{dx^2} = \sqrt{(R + j\omega L)} \quad \sqrt{(G + j\omega K)}$$

and an identical equation for $I$.

Let use designate by—

$$P = \sqrt{(R + j\omega L} \quad \sqrt{(G + j\omega K)}$$
$$P = \alpha + j\beta$$

As the product of the vectors under the radicals must be a complex number or a "vector" quantity— a directional quantity—we have written it in the usual algebraic form $\alpha + j\beta$. Now substitute,—

$$R = G \tan \alpha$$
$$L = K \tan \alpha$$

Hence,—

$$P = \sqrt{(G + j\omega K) \tan \alpha}\ \sqrt{(G + j\omega K)}$$
$$= (G + j\omega K) \sqrt{\tan \alpha}$$
$$= \alpha + j\beta$$

Hence,—

$$\alpha = G \sqrt{R/G} = \sqrt{RG}$$
$$\beta = \omega K \sqrt{L/K} = \omega \sqrt{LK}$$

An inspection of Fig. 1 shows that the real part of $P$ affects the magnitude only of $E$ and, therefore, it has been designated as the attenuation constant $\alpha$. It is independent of the frequency. The imaginary part, or the part in time quadrature with the e.m.f., represents a propagation constant $\beta$ which does not affect the strength of the signal or the current, but which—in a circuit in which there is distortion—would "mix up" the signals, as Heaviside used to say. In the distortionless circuit the velocity of propagation is equal to $\frac{1}{\sqrt{LK}}$ and also independent of the frequency.

Thus, by balancing the leakage of the circuit against the resistance component of the e.m.f., and balancing the charging current against the inductance component, Heaviside devised a circuit over which all signals, whatever their frequency, would travel at the same speed. This must be so, as the phase relations at any part of the circuit between e.m.f. and current remain the same as at the starting point which is the receiving end in the case under consideration.

*(To be Continued)*

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# Some Transmission Line Fundamentals

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THE increasing importance of the high-tension transmission of power carries with it an ever-increasing interest in the mechanism of transmission. The rapid increase in line voltage, together with the increase in length of lines, brings out features of transmission line phenomena not formerly well understood and recognized. The application of high-frequency currents to telephone communication over high-voltage power lines also serves to bring out some of the general phases of the transmission line problem.

The technical analysis of the problem of transmission has been thoroughly worked out and made available for everyday engineering application. The first important contribution to the theory of transmission of electric currents over wires was made by Oliver Heaviside. The work of Heaviside has been put into a form where it is now available for ordinary engineering calculations. This advance was accomplished by the application of hyperbolic functions to the problem by Kennelly, Fleming and others. Although this work is available, it is felt that an elementary presentation of some of the leading ideas in transmission line theory might be acceptable to those engaged in transmission line work and who have not the time to dig it out of the original treatises.

In the transmission of power over short lines at power frequencies, the resistance and the inductance of the line are the only factors which need to be taken into account in determining the performance of the line. The well known Mershon diagram for calculating line regulation assumes that a line possesses only resistance and inductance. When lines are operated at high voltage and are of considerable length, line capacity is sometimes taken into account. This is usually accomplished by conceiving the distributed capacity of the line to be lumped at the ends, half of the total line capacity being placed at each end. When the power line is energized from the generating end and open at the receiving end, it is known that the terminal or receiving-end voltage is greater than the sending-end voltage. This is accounted for by noting that the charging current of the receiving-end condenser is drawn through the line inductance. Being a leading current, this adds to the generator voltage.

The foregoing view of a line is entirely satisfactory for most practical purposes at power frequencies. It is not generally appreciated, however, that these ideas apply only to a limited and, in fact, a very small part of transmission line phenomena. If the length of the line is increased a hundred or a thousand times, or if the frequencies are increased a hundred or a thousand times, the conceptions which are entirely satisfactory in dealing with short lines at power frequencies are no longer adequate. For example, with frequencies of the order of 60 000 cycles, it is found by actual measurement that a line is not always a capacity when the receiving end is open. In fact, the line changes periodically from an inductance to a capacity as the frequency is progressively increased. Thus any given line will act on the sending end generator as a resistance, an inductance or a capacity, depending on the length of line and the frequency applied.

If the conceptions which apply to short lines were used in dealing with long lines, the capacity effect of the long line would be obtained by multiplying the capacity per mile by the length of the line. Thus a line of infinite length would have an infinite capacity. The fact is that an infinite line, or a line so long that terminal conditions at the distant end have no effect on the sending end, acts on the sending-end generator like a nearly pure resistance of the order of 600 to 850 ohms. The precise value of this resistance depends on the size and spacing of the conductors. This is in rather startling contrast to the conclusions which would result from applying the methods of analysis ordinarily used in dealing with power transmission problems.

The reason that the more elementary analysis commonly used in calculating transmission line regulation does not apply to very long lines, or to lines working at high frequency, is because no account is taken of velocity of propagation and because the line resistance, inductance and capacity are not lumped as the elementary analysis assumes, but are uniformly distributed over the length of the line. The velocity of propagation of electricity over wires is so great that, for most ordinary purposes, it is assumed to be instantaneous and is left out of consideration. It is only for lines of great length or for high frequencies that velocity of propagation requires consideration. For lines operated at commercial frequencies and of a length realized in present-day practise, the potential of all parts of the system rises and falls substantially in unison. This means that the electric charges produced by the generator have time to run down the length of the line, be reflected and returned to the generator again before the generator has time to move through an appreciable electrical angle. If the generator frequency is gradually increased, or if the line be lengthened, it will be apparent that the charges leaving the generator at a given instant will return to the generator after reflection at the distant end to find the generator in a new angular position. The farther the generator has rotated during the propagation down the line and return, the more pronounced will be the difference between the results calculated by

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the elementary theory of transmission lines and the actual line.

### PROPAGATION OF ALTERNATING CURRENTS ON AN INFINITE LINE

In the study of lines, especially when transmitting high-frequency currents, their properties are more easily understood when the length is made infinite. The behavior of an infinite line is much more simple than that of a finite line, because it is not complicated by reflections from the end. With such a line all disturbances originating at the sending end are propagated down the line, but can never return to combine with, and interfere with the advancing waves coming from the sending-end generator.

When alternating currents are propagated down an infinite line, the amplitude of the voltage vector is progressively reduced the farther the distance from the sending end. The percentage decrease in amplitude per mile is a constant throughout the length of the line. The amplitude of the voltage vector at a point $x$ miles from the sending end may be expressed as,—

$$E_x = E_0 \epsilon^{-ax} \quad \text{.....(1)}$$

The reduction in amplitude per mile is given by the factor $\epsilon^{-a}$. It is the attenuation ratio per mile of line. The exponent $a$ is the attenuation constant.

In addition to being progressively reduced in amplitude, the phase of the voltage vector is progressively shifted backwards as the distance from the sending end increases. That is, the vector representing the potential between wires at a given point on the line differs in phase from the vector representing the potential at a point farther down the line. The potential at the more distant point always lags behind the potential at a point nearer the sending end. This phase displacement is the same for each mile of line, that is, it is a constant. The phase lag per mile is called the wave-length constant. The phase lag of the voltage vector at a point $x$ miles from the sending end is,—

$$\theta = bx \quad \text{.....(2)}$$

where $b$ is the wave-length constant.

The attenuation of the voltage or current vectors as well as the retardation in phase, can be represented diagrammatically as in Fig. 1. The line conductors are represented by $A$ and $B$. The potential between lines at the point $O$ is represented by the length of the vector $E_0$, which is drawn vertically as a position of reference. At points representing one mile intervals circles are drawn whose radii are progressively reduced by the factor $\epsilon^{-a}$. Thus the radius of the circle at the end of the first mile is $E_0 \epsilon^{-a}$. The circle at the end of the second mile is $E_0 \epsilon^{-2a}$, etc. The circle at the distance $x$ is defined by equation (1). The voltage vector at the end of the first mile is drawn so as to lag behind $E_0$ by the angle $b$. The voltage vector at the end of the second mile lags by the angle $2b$, etc.

The potential at the point $x$ may be completely represented by combining equations (1) and (2) thus,—

$$E_x = E_0 \epsilon^{-ax} \cdot \epsilon^{-jbx} \quad \text{.....(3)}$$

The factor $\epsilon^{-jbx}$ is an operator ($\cos bx - j \sin bx$) which rotates the vector on which it acts through the angle ($-bx$). It performs the operation required by equation (2) in that it locates the vector $E_x$ behind $E_0$ by the angle $bx$. The whole expression therefore gives the vector $E_x$ both in magnitude and in phase with respect to $E_0$. Adding the exponents in equation (3) gives:—

$$E_x = E_0 \epsilon^{-Px} \quad \text{.....(4)}$$

where $P = a + jb$. The quantity $P$ is known as the propagation constant. It may be demonstated to be[1]:—

$$P = \sqrt{R + j\omega L} \ \sqrt{G + j\omega C} \quad \text{.....(5)}$$

where $R$, $L$, $G$ and $C$ are the fundamental constants of the line per unit length.

The current in an infinite line is attenuated just like the voltage. The current at any point in the line without regard to phase is expressed by an equation similar to equation (1).

$$I_x = I_0 \epsilon^{-ax} \quad \text{.....(6)}$$

If we insert an ammeter at the sending end and another at a point in the line $x$ miles away, we can use the

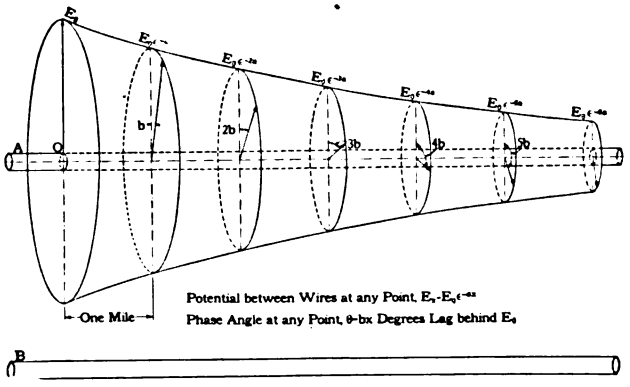


FIG. I—PHASE AND POTENTIAL AT VARIOUS POINTS ALONG A LINE

ratio of these two readings to determine the attenuation constant $a$, thus,—

$$\frac{I_2}{I_1} = \epsilon^{-ax} \quad \text{.....(7)}$$

from which we get the attenuation constant,—

$$a = \frac{\log_{10} \frac{I_1}{I_2}}{0.4343\, x} \quad \text{.....(8)}$$

This equation is of importance since it enables us to determine the attenuation constant by making observations on the line.

### INFINITE LINE

With an infinite line supplied by a generator $G$, Fig. 2, it is apparent that when impressing a given potential on the line terminals at $A$, the generator will cause a certain current to flow into the line which may be expressed by equation (9).

$$I_0 = \frac{E_0}{Z_0} \quad \text{.....(9)}$$

The line under consideration may have any charac-

[1]See "Propagation of Electric Currents" by Fleming.

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teristics whatsoever so long as it is uniform; that is, so long as the resistance, inductance, capacity and leakance per mile are constant. The current entering the line from the generator may lead or lag the generator impressed voltage by any angle, depending entirely upon the inherent characteristics of the line arising from the line constants $R$, $L$, $G$ and $C$. Thus equation (3) is a vector equation in which the quantity $Z_0$ is an impedance determined from the observed magnitude and phase of the impressed current and voltage.

If now the generator is moved down the line to any new point $P$ and the section of the line to the left of $P$ cut off and only the infinite part to the right of $P$ retained, the generator will feed exactly the same current into the line at the same voltage as at location $A$. This becomes obvious because the line extending to the right of $P$ is infinite and is, therefore, the same line as that to the right of $A$, which was also infinite in the previous test. Since the generator is feeding into an impedance of the same value at $P$ as it did at $A$, the same current must flow. It does not matter how far the point $P$ is moved down the line from the initial position $A$, the impedance load imposed on the generator will always be the same, provided the section to the left of $P$ is always cut off during the test. It is to be carefully observed that the resistance and reactance between the points $A$ and $P$ does not, in any way, diminish or alter the impedance as measured at P.

## CHARACTERISTIC IMPEDANCE

The quantity $Z_0$ as defined above is a very important quantity. It is called the "line characteristic impedance", sometimes the "surge impedance" or more briefly "line characteristic". It enters into all transmission calculations. It is the impedance of a line of infinite length as measured at the sending end.

Suppose that by measurement it is possible to determine the value of $Z_0$ and that this value of impedance is placed across the line at any point $P$ and the infinite line remaining to the right of $P$ is cut off, the generator being at $A$. The generator will then feed current into the line at $A$ just as though it were feeding into the original infinite line, since the infinite line has been replaced at $P$ by its equivalent impedance. Thus

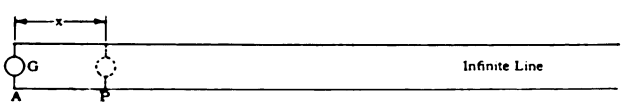


FIG. 2—AN INFINITE LINE SUPPLIED BY A GENERATOR

The current entering the line at $A$ is $I_0 = \frac{E_0}{Z_0}$, where $Z_0$ is a vector which may have any angle of lag or lead, depending on line constants.

the current entering the line is again determined precisely by equation (9). It is of interest to note that for any finite line terminated in its characteristic impedance no matter how long or how short, the current entering the line from the generator is always determined by equation (9). This is true notwithstanding the fact that there may be hundreds or thousands of ohms in the finite section of line between $A$ and $P$. The generator at $A$ will always feed into an impedance $Z_0$.

## SIMPLE METHOD FOR DETERMINING CHARACTERISTIC IMPEDANCE FOR HIGH FREQUENCIES

As pointed out above the impedance of a finite line from the sending end, will be the characteristic impedance, provided the distant end is closed through an

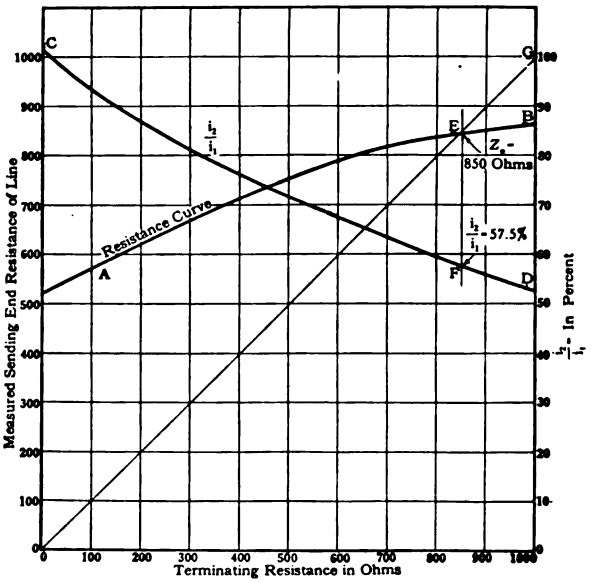


FIG. 3—CHARACTERISTIC RESISTANCE AND ATTENUATION RATIO

For the circuit shown in Fig. 4, 60 miles long, tested at 66 000 cycles. $I_2/I_1 = \epsilon^{ax} = 0.575$
Attenuation constant $a = 0.00923$
Effective resistance per mile of line $R = 2\,aZ_0 =$ 15.7 ohms
D.C. resistance per mile of line = 0.458
Calculated A.C. resistance = 6.3
Ratio $\frac{\text{Observed A.C. res.}}{\text{Calculated A.C. res}} = 2.5$

impedance equal to the characteristic impedance. If therefore an impedance can be found such that, when it is bridged across the open end of a finite line, the measured sending-end impedance is equal to it, then this impedance is the characteristic impedance of the line. The method then is to place a trial impedance across the open end of the line under test, and measure the impedance at the sending end. The terminating impedance is varied until the impedance measured at the sending end is equal to it. The terminating impedance is then the characteristic impedance of the line and the ratio of received to sending-end current gives the attenuation ratio correctly.

For work on overhead lines at high frequencies, this method is easily carried out in practise, since in this case the characteristic impedance is always a simple non-inductive resistance. This can be seen by inspection of the equation for characteristic impedance in terms of the fundamental line constants,—

$$Z_0 = \frac{\sqrt{R + j\omega L}}{\sqrt{G + j\omega C}} \qquad (10)$$

At high frequencies the value of $R$ is always negligible when compared to $\omega L$, and $G$ is negligible when compared to $\omega C$. The equation therefore reduces to,—

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$$Z_0 = \sqrt{\frac{L}{C}} \quad \text{.....(11)}$$

Since the $j$ component does not appear, the quantity is a pure resistance. Hence for work at high frequencies on open wire lines, it is known beforehand that the characteristic impedance is a resistance. The trial terminating impedance, therefore, is a simple non-

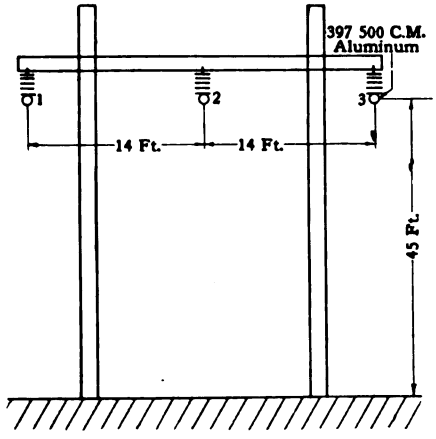


FIG. 4—CONFIGURATION OF TRANSMISSION LINE

inductive resistance. The work of measurement at the sending end is also simplified since it is known that when the correct adjustment is reached, the sending-end impedance will contain no reactive component. Hence only the resistance component of the sending-end impedance need be measured.

In actually determining the characteristic impedance of a line under test, a series of values of terminating resistance are used. For each value of terminating resistance, the corresponding sending end resistance is measured. These data are then plotted as shown in Fig. 3. The terminating resistances are plotted as abscissae and the measured sending-end resistances as ordinates. The curve $AB$ is then drawn through these points. The characteristic resistance is represented by a point on this curve whose co-ordinates are equal. This point may be determined by drawing the line $OG$ so as to bisect the right angle at $O$. The co-ordinates of any point in this bisector are equal. Hence the intersection of $OG$ with the resistance curve $AB$ determines the point $E$, whose abscissae or ordinates are each equal to the characteristic impedance. The characteristic impedance for the line shown in Fig. 3 is 850 ohms.

In taking the data for the resistance curve, ammeters are placed at the sending and receiving ends. Readings of these meters are taken for each value of terminating resistance. The ratio of these currents $\frac{I_2}{I_1}$ is then plotted as curve $CD$, Fig. 3. The received currents for any value of terminating resistance can then be determined from this curve. The ratio of received to sending currents, for the case where the line is determined in its characteristic impedance, is determined by drawing a vertical line through $E$. Its intersection $F$ with the curve $CD$ gives the attenuation ratio. The value of the attenuation ratio for the line under consideration is 57.5 percent.

The line to which the data in Fig. 3 applies is a single circuit three-phase line, whose configuration is given in Fig. 4. The test was made on a metallic circuit formed by using the two outside wires 1 and 3. The frequency used was 66 000 cycles per second. The conductors were 397 500 cir. mil aluminum steel-reinforced. They consist of thirty strands of aluminum and seven strands of steel, the outside diameter being $\frac{7}{8}$ inch.

### WAVE LENGTH CONSTANT

The wave length or phase-constant $b$ is determined from the frequency and velocity of propagation. If the velocity of propagation is known, the wave length in miles may be determined by dividing the velocity by frequency as in equation (12).

$$\lambda = \frac{V}{f} \quad \text{.....(12)}$$

This is derived from consideration of Fig. 5 which represents a section of line of length $V$ equal to the velocity of propagation. In one second the generator would send into the line a number of cycles $f$ which are distributed uniformly over the length $V$ which is the distance to which the first part of the first cycle would have traveled in one second. The generator is at this instant imposing the final part of the last cycle, at the generating end. Obviously the distance between two zero points is obtained by dividing the number of waves, that is cycles on the line, into the length $V$ occupied by those waves. A wave length represents a complete cycle, that is a full revolution of a two-pole generator. The vector representing voltage at a point on the line distant from the generator one wave length will lag one revolution behind the generator. The phase constant $b$

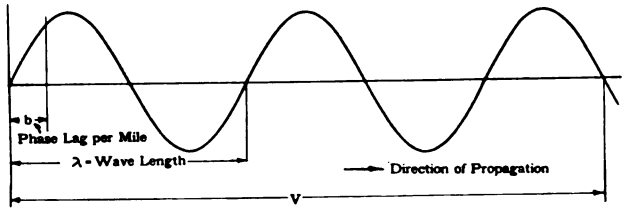


FIG. 5—SECTION OF TRANSMISSION LINE

$$\lambda = \frac{V}{f} = \frac{\text{Distance Traveled in One Second}}{\text{Generator Frequency}}$$

b $\lambda = 2\pi$; that is, degrees lag per mile times miles in one wave equal one revolution or $2\pi$ radiaus.

is the angle of lag per mile of length. The lag per mile multiplied by the number of miles in a wave length must give one revolution, that is 360 degrees or in circular measure is expressed as $2\pi$. This gives equation (13),—

$$b\lambda = 2\pi \quad \text{.....(13)}$$

from which equation (14) follows:—

$$b = \frac{2\pi}{\lambda} = \frac{2\pi f}{V} \quad \text{.....(14)}$$

*(To be Continued)*

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# New 40000 Kilowatt Turbines for the Duquesne Light Company

J. D. SCHMIDT
Engineering Department, South Philadelphia Works
Westinghouse Electric & Mfg. Co.

AS part of its program of expansion, the Duquesne Light Company of Pittsburgh has contracted for two new turbine generator units to be placed in their Colfax Station. One of these machines is now in course of erection. The turbines are rated at 40 000 kw, and are connected to generators rated at 48 500 kv-a at 80 percent power-factor. No direct connected exciters are provided. The operating conditions are 260 lbs. gauge pressure at the throttle with 214 deg. F. superheat and a back pressure of one inch of mercury, absolute. Arrangements are provided for bleeding the turbines at four points for feed water heating.

The structure of the turbine cylinder and rotor, and the type of blading arrangement, are similar to a large number of 20 000 and 30 000 kw units built in recent

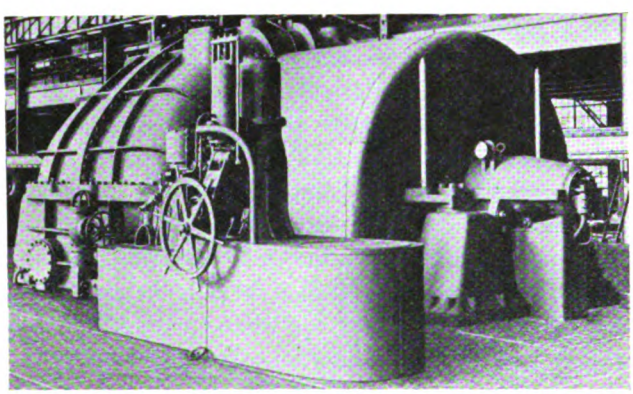

FIG. 1—THE NEW 40 000 KW, 3600 R.P.M. STEAM TURBINE

years. In details, however, the design has been vitally modified. Some of these features are novel, especially the governing devices and the arrangements for supporting the turbine on the foundation.

A sectional view the general design is shown in Fig. 2. The cylinder consists of a steel, high-pressure portion divided into upper and lower halves, and a cast-iron low-pressure portion similarly divided, but also divided vertically in the transverse plane through the center of the exhaust opening, in order to overcome shipping problems and to bring the weights of the parts within the capacity of power-plant crane facilities.

The blading is of the combined impulse and reaction type. The intermediate pressure stationary reaction blading is carried in blade rings secured to the cylinder by means of a flexible construction which permits differential expansion of the cylinder and ring without danger of distortion of the ring. The low-pressure blading is of the multi-exhaust type with stationary blades secured to the cylinder proper. The last row of guide vanes, however, are cast in sections which are held in place in the cylinder by means of an interlocking joint and cap screws. The high-pressure rotating reaction blades are secured in the rotor by means of dovetail packing pieces holding upset projections on the ends of the blades. The low-pressure rotating blades are held in T-shaped grooves in the rotor. The impulse blading is of the customary two-velocity single-pressure stage type.

Provision for differential expansion is made in the case of the nozzle chambers, and the design is such that the steam inlet pipes are bolted to flanges on the chambers, rather than directly to the cylinder.

Part of the end thrust, due to the pressure drop across the reaction blades is balanced, in accordance with usual practice, by balance pistons or dummies, and the remainder is carried by the Kingsbury thrust bearing. The cylinder dummy rings are secured to the cylinder by means of the same type of flexible connection employed in the case of the blade rings and the balance pistons are formed as integral portions of the rotor. The labyrinth seal is formed by grooves in the piston and by solid radial packing strips in the dummy rings, so arranged as to clear the rotor ridges, or lands, by a small clearance which can be adjusted by end motion of the rotor in the cylinder.

Water sealed glands are provided to prevent leakage of air or steam into or out of the turbine where the rotor shaft extends through the ends of the cylinder. Water supplied to the gland casing at a pressure of about 15 lbs. per sq. in. is held radially outward by the pumping action of a runner mounted on the shaft and forms an annulus of water around the periphery of the runner, thus sealing the space between runner and casing against the passage of air or steam.

An interesting feature is the construction of the Kingsbury thrust bearing, the collar of which is made to do double duty as an oil impeller in connection with the governing and lubricating system. This collar is an integral part of the turbine shaft, and is considerably thicker than would be necessary were thrust carrying its only duty. From the end of the shaft a bored passage communicates with a series of radial holes drilled in the collar. In this manner the thrust collar is made to serve as a pump runner to supply oil to the governing system. The thrust bearing is in other respects of familiar design.

### GOVERNING BY OIL PRESSURE

The most outstanding feature of the design is the

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governor, which is of a type but recently applied to units of such size, although it has been used in connection with 3600 r.p.m. turbines of moderate size for a number of years. In this design the governing force is oil pressure created by the centrifugal action of the impeller mounted on the turbine shaft, and the functions of governing and lubrication are tied together in a simple

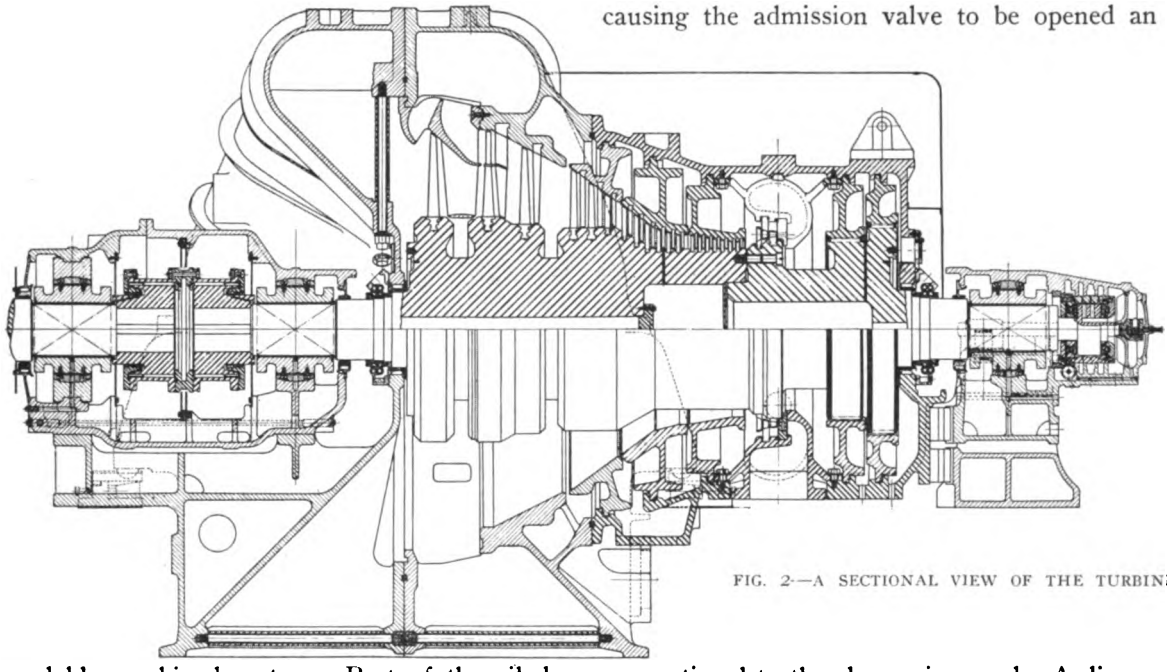

FIG. 2—A SECTIONAL VIEW OF THE TURBINE

and dependable combined system. Part of the oil delivered by the impeller is taken to serve as motive oil for an ejector mounted on the oil reservoir and a further amount passes through a throttling orifice into the lubricating system. The ejector delivers low-pressure oil to the impeller suction chamber and serves to maintain a constant positive pressure therein.

In the governing device proper, Fig. 3, the oil pressure, which varies as the square of the revolutions per minute, is opposed by the tension of a coil spring in a relay which actuates a control piston in the operating cylinder located on the steam chest. Increase in the impeller oil pressure, due to increase of turbine speed, causes motion of the relay upward and thereby admits oil to the upper part of the operating cylinder and releases it from the lower part. This causes the operating piston to move downward, partly closing the admission valves. Reduction in speed is accompanied by reduction in oil pressure and, in this case, the movement of the several parts is therefore in the reverse direction, causing the admission valve to be opened an amount proportional to the change in speed. A diagram of the oiling system is shown in Fig. 4.

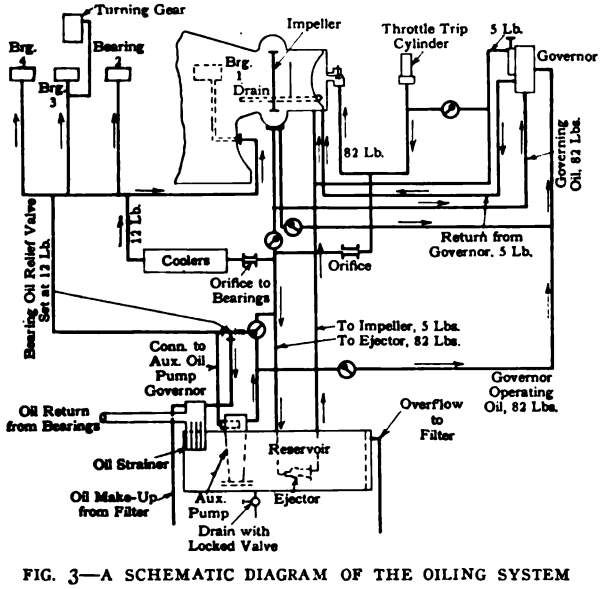


FIG. 3—A SCHEMATIC DIAGRAM OF THE OILING SYSTEM

The experience of over four years of operation with 3600 r.p.m. turbines equipped with impeller-type oil governors indicates a considerable increase in the life of the lubricating oil. This is attributable to the deaerating effect on the oil of the particular construction of the impeller.

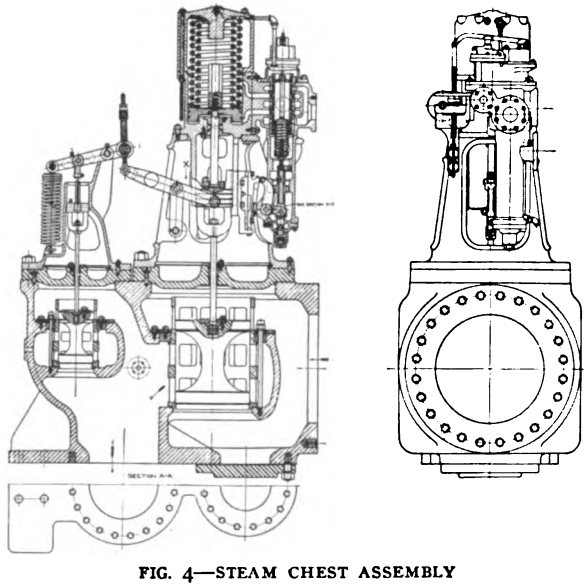

FIG. 4—STEAM CHEST ASSEMBLY

The impeller is designed with several times the capacity required for governing and lubrication, but the outlet passage from the impeller chamber is of the area required to pass the amount of oil needed for the system. Consequently, the velocity of passage through the im-

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peller is low; so low that any air entrained with the oil, having a much lower specific gravity, is forced toward the center of the impeller and escapes through a passage provided for the purpose. As a result, the air entrained during the passage of the oil through the lubricating system is continually removed and, therefore, oxidation of the lubricant is reduced to a minimum.

The governor relay chamber is so designed that the face of the relay sleeve, or piston, not exposed to the governing oil pressure, is subjected to a back pressure which is controlled by an adjustable relief valve. Variation in this back pressure has the same effect as variation of the relay spring tension and produces a corresponding change in speed. By means of this relief valve, the back pressure may be changed at will and this valve adjustment is arranged to be operated either by a hand wheel or by a motor which can be furnished with remote control. In this manner a simple and sensitive speed changer device is provided by means of

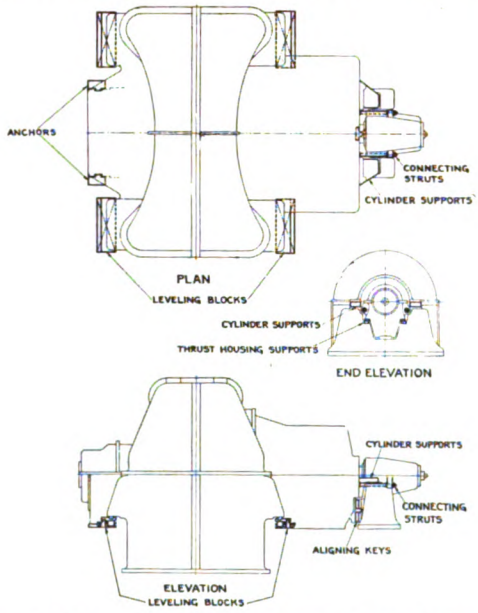


FIG. 5—PLAN AND ELEVATION VIEWS OF THE TURBINE

which the 10 percent range of speeds required for synchronizing may be obtained.

Protection against damage due to loss of oil is afforded by the provision of a low-pressure oil relay, in which a relay plunger is held in normal position by oil at impeller inlet pressure opposing the force of a compression coil spring. If the impeller inlet pressure is reduced below a predetermined safe amount, the spring moves the relay plunger into position to cause the closing of the governor controlled admission valves.

### METHOD OF ALLOWING FOR EXPANSION

Of equal interest and of great importance to the successful operation of the turbine, are the means provided for free expansion of the turbine parts with reference to the supporting members, without imposing undue stresses upon the parts and without disturbing the alignment of turbine and generator.

Briefly, the coupling end of the turbine rests on four chairs at the four corners of the exhaust casing, while the thrust end is free to slide on supports in the thrust bearing housing pedestal, which is rigidly secured to the foundation. The four exhaust casing chairs are carried on leveling blocks fitted with semi-cylindrical pivot blocks, and the corners are free to expand in any direction. The coupling end pedestal is overhung from the exhaust structure and is restrained from moving sidewise or longitudinally by gibs or anchors bolted to the foundation.

The thrust end of the cylinder is borne by two pads resting on brackets formed in the sides of the thrust end bearing pedestal. Thus the cylinder is free to move endwise with reference to the latter. The thrust-bearing cage is carried by a secondary pedestal, within the thrust-bearing housing pedestal proper, and is likewise free to slide endwise. The thrust bearing housing is secured to the cylinder structure by means of two long strut bolts.

Sidewise alignment of the cylinder at the thrust end is obtained by means of centering keys which are held in suitable recesses in the pedestals, thus permitting unrestricted vertical or longitudinal expansion, but preventing side-movement. The support arrangement is illustrated in Fig. 5.

The generator inboard bearing is carried in the coupling-end turbine bearing pedestal and the turbine and generator are connected by a toothed flexible coupling.

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## An Arc-Welded Bridge

THE historically famous Turtle Creek at East Pittsburh, Pa. has witnessed another event which marks the opening chapter of a new field of history—arc-welded bridges.

A new railway bridge was needed across the creek, so, instead of constructing one of the conventional riveted design, the main girders, floor beams and stringers were arc welded together to form a one-piece structure. As much of this welding was done in the shops as was possible, considering the capacity of the locomotive cranes. Thus

FIG. 1—ARC WELDERS REPLACE RIVETERS ON THIS BRIDGE

the bridge was built into place in relatively large pieces in a day and a half, four arc welders doing the job.

The new bridge, 62 feet long, contains 20 tons of steel. This weight is about fifteen percent less than that of an equivalent riveted structure. For larger bridges the percentage of saving will be even greater. To take fullest advantage of this important saving requires completely new bridge designs, as a welded structure and a riveted structure provide for the load stresses quite differently.

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# Oscillography

## VIII.--Auxilliary Apparatus for Staged Tests with the Multi-Element Oscillograph

JOSEPH W. LEGG

THE earliest forms of oscillographs gave fairly satisfactory records of recurrent phenomena, such as voltage and current wave-forms of generators. Today the operating engineer of a great central station or electric railway cares little for an oscillograph which will not record tansient conditions in a reliable manner. He specifies that the wave-form of each generator shall conform to certain limits as to harmonics; however, he cannot be certain what transient conditions may arise in his system to cause the system wave-form to be very poor, either momentarily or over a considerable period of time. This poor wave-form may be caused by a customer's apparatus which may cause much trouble, and possibly heavy loss, to another customer or to the central-station itself. The oscillograph will often show up this trouble and enable it to be eliminated before any real damage is done.

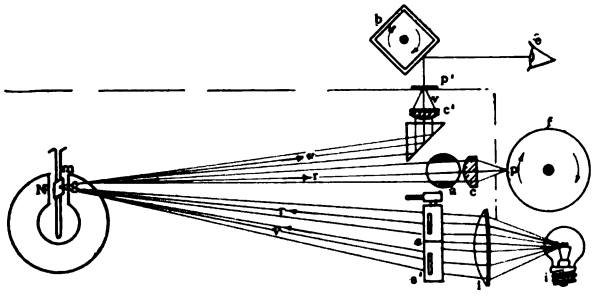

FIG. 1—SCHEMATIC DIAGRAM FOR SIMULTANEOUS VIEWING AND PHOTOGRAPHING

*i*—incandescent lamp illuminant; *m*—vibrator mirror; *l*—spherical condensing lens; *s*—vertical slots; *f*—photographic film; *p*—point of light on film; *p'*—point of light on ground glass; *c*—cylindrical condensing lens for film; *c'*—cyclindrical condensing lens for viewing system; *b*—polygon of mirrors to give time component to waves being viewed; *e*—observers eye; *r*—recording beams of light; *v*—visual beams of light; *a*—shutter open only during photographic operation.

A disturbance in wave forms may occur but a few minutes per day, as when some customer is starting up a certain machine or is passing through a certain process in manufacture. Often its origin is not known, even when the results are striking.

As an example of this, certain high-voltage testing transformers acted peculiarly at times and even broke down at relatively low voltages. After several expensive breakdowns it was decided to set up the incandescent-lamp oscillograph and observe the supply wave-form continuously. Many oscillograms had been taken before this, but none showed any bad harmonics in the supply potential waves. Continuous visualization showed that occasionally the supply wave-form showed prominent harmonics even when the high-voltage testing transformers were not being used. These transients lasted for such a short time that it was impossible to change over from the viewing attachment of the oscillograph to the photographing attachment quickly enough to catch the main disturbance.

A simultaneous viewing attachment has been developed which permits the operator to view the potential, current, power, vibration or pressure waves in the rotating polygon of mirrors, for any length of time, until an unusual wave form appears. By a twist of the wrist, the operator can almost instantly cause the oscillograph to photograph the wave-form desired while he continues to view it in the mirrors. A high-speed record may be taken on a film 10 inches long, in a small fraction of a second, or repeated slow-speed records may be taken with a total length of 8 or 24 feet. In the latter case the record may be stopped whenever the operator sees

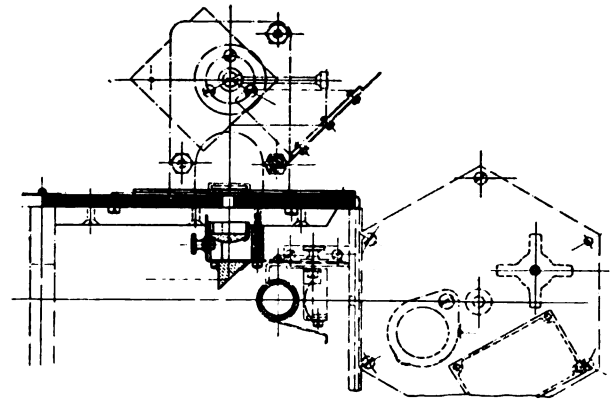

FIG. 2—SIMULTANEOUS VIEWING ATTACHMENT

fit. Viewing may continue unbroken and photographing resumed at will.

The simultaneous-viewing attachment is valuable in other applications; e.g., recording transitory pressures, water hammer in pipes and turbines, vibrations in machines passing through critical speeds, earth vibrations resulting from a distant explosion, telephone interference, critical vibrations in a railway bridge, etc.

A schematic diagram of apparatus used in simultaneous viewing and photographing is shown in Fig. 1. The light from the incandescent lamp *i* is condensed by *l* so as to pass through the two slots *s'* and *s* (one above the other) to the vibrator mirror *m* whence it is reflected in two ribbon-like beams, one of which, *v* is reflected upward by the prism through the extra cylindrical lens *c'* to the ground glass at *p'*. The rotation of the mirrors *b* stretches the point of light out into a line which takes the form of waves of light when the mirror *m* vibrates as a function of the instantaneous values of

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current which pass through the vibrator strips. The lower ribbon of reflected light *r* passes to the shutter *a* and thence on to the photographic film *f* at *p*. For high-speed records *f* rotates continuously and *a* opens during one revolution when released by the observer.

Actually there are nine vertical prisms between *i* and *s*, *s'* etc., so that there may be six photographic records and three simultaneous waves for viewing. The 7th, 8th and 9th galvanometers cannot be used when three waves are being simultaneously viewed. The corresponding adjustable slots are raised out of their normal positions, and are shifted slightly forward and to one side[1] (in cavities provided) so that the 7th, 8th and 9th reflecting prisms cast extra beams on three of the vertical-type galvanometers. Thus each of these three galvanometers may be adjusted to give simultaneous visual and photographic records. The viewing attachment may be operated by hand or from a small motor.

### CHOICE OF GALVANOMETER ELEMENTS

The complete six-element galvanometer having the vertical type of vibrators is shown in Fig. 3. A spare vibrator is shown at one side. Each one of the six units is complete in itself, including the permanent magnet. Either a standard or a sensitive vibrator may be used. The standard vibrator has an undamped frequency of vibration of approximately 5000 cycles, but when immersed in the transparent oil, it gives practically the same deflection for all frequencies from 25 to 2500 cycles per second, and shows up frequencies as high as 15 000 and even 20 000 cycles per second. This standard vibrator requires approximately 0.12 ampere per inch deflection with direct current, and has a resistance of approximately one ohm.

The sensitive vibrator requires approximately one-fifth the current of the standard, covers about half the

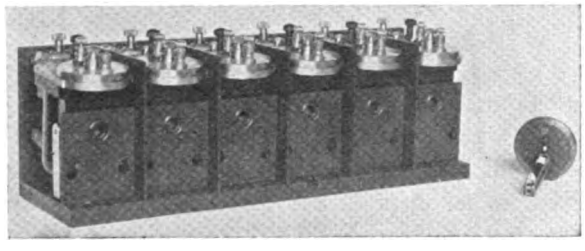

FIG. 3—A COMPLETE SIX-ELEMENT GALVANOMETER
With extra vibrator at one side.

range of frequency and has approximately sixty percent greater ohmic resistance. Both vibrators are non-inductive. The sensitive vibrator covers the range of frequencies met in power circuits well, except for high-speed records where it is desired to record the highest harmonics. The standard vibrator is slightly more rugged than the sensitive one, since its ivory bridges are but half as far apart, and its vibrator strips are approximately 50 percent thicker. If not more than 1000 percent above normal current is passed through these strips, the spring-tension fuse (of same material in air) will usually protect them.

The sensitive vibrator is usually chosen for the instantaneous wattmeter, since it is often impracticable to operate the field winding at rated current for all tests. Also for high-voltage tests, where no potential transformer can be used (such as in measuring potentials in rectifier circuits, etc.) it is often desirable to use the sensitive vibrator, so as to reduce the power wasted and

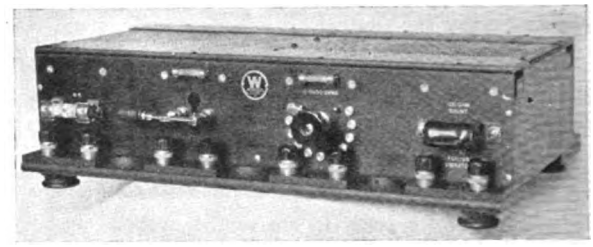

FIG. 4—EXTERNAL RESISTOR
With four units of 5000 ohms each.

the corresponding heating of resistors. In electric-car tests, the sensitive vibrator may show signs of mechanical vibration during photographic recording, due to the jolting of the car or from other vibrations. Usually, this forced vibration can be eliminated, if the operator takes due care in cushioning the apparatus. The standard vibrators show no signs of forced vibration, when the operator uses care, even though the oscillograph is being used to record reversing operations, braking, etc., in a swiftly moving electric car.

### EXTERNAL RESISTOR APPLICATIONS

In Fig. 4 is shown a 20 000-ohm non-inductive external resistor which may be used with any oscillograph to obtain tests on rectified or direct-current lines of from 500 to 3000 volts. This resistor unit is the same size as that which fits under the galvanometer compartment of the multi-element oscillograph, with a top and bottom added. It includes 40 thin micarta plates, wound with 500 ohms each of copper-nickel wire. This arrangement makes the resistors practically non-inductive and presents considerable heat radiating surface. There are four units of 5000 ohms each, one of which is adjustable in 500-ohm steps. This resistor unit is not intended for continuous operation except for supplying two sensitive vibrators, with 10 000 ohms in series with each, on 500 or 600 volts. It will operate one vibrator on 3000 volts, or two vibrators on 1500 volts each, for short periods during photographing or calibration.

Great care must be used when studying high-voltage circuits backed with real power. Additional external switches and fuses should be used in high-voltage power tests. The switch shown in the illustration, may be used up to 600 volts, and even for 1500 volts for laboratory tests on direct-current and audiofrequency circuits in radio broadcasting, etc.

The 100-ohm shunt at the right should be connected

[1]See Figs. 6 and 7 pp. 560 and 561 Oscillography—VI in the November 1927 issue of the JOURNAL.

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between the resistor and ground, with the oscillograph vibrator connected in series with an adjustable low resistance and thence across this shunt. Thus if the vibrator circuit becomes opened the oscillograph will still remain within a few volts of ground.

Inductive kicks in direct-current and rectified-current lines are often many times normal voltage. In quick-acting circuit breakers, the inductive kick of potential is sometimes 5000 volts from a 500-volt line. The oscillograph vibrator must have resistance enough in its circuit to retain the deflection on the film in order to read the peak value. This often makes it advisable to use this external resistor unit in studies on even 500-volt lines. However the resistance in the standard multi-element oscillograph is usually enough for such momentary studies (not over 600 volts normal) provided the standard vibrator is used to limit the deflection on voltage surges, or provided a small shunt is placed across the sensitive vibrator, and the vibrator is kept near ground potential.

*Water-Column Resistors*—A high-voltage resistor may be made from a garden hose, metal fittings and a supply of running water. When the voltage to be studied is high and uni-directional[2], or whenever it is not feasible to use potential transformers, a water-column resistor will be found to be more satisfactory than wire-wound resistors of more than 20 000 ohms. Such water-column resistors have been used for continuous operation in circuits up to 220 000 volts. Fig. 5 shows the general arrangement of a running-water-column resistor. Such resistors have very little distributed capacity and inductive reactance, and hence introduce a minimum of error in the records of high potential. The ohmic resistance of drinking water varies considerably in different localities, and even varies slightly hour-by-hour in most localities. However oscillograph records are usually taken to show the instantaneous variations in voltage and not the absolute values. Except for recording absolute values of voltage the water-column resistor is ideal.

The values given in Fig. 5 are for the standard vibrator. If the sensitive type of vibrator is used, the resistance should be approximately five times as great, or the sensitive vibrator should be shunted by a resistance so as to reduce the deflection on the film to the desired value. For the higher resistance and lower current, a smaller internal-diameter hose can be used. The water flows through the rubber hose from ground potential up through the metal insert, which is connected to the oscillograph vibrator, and on up to the high-voltage metal insert and then down to ground again. If a metal insert in the return is also connected to the same terminal of the vibrator the current in the oscillograph vibrator will be doubled. If intermediate inserts are used, half way to the high-voltage insert, then the vibrator current will be doubled again. With the arrangement shown, four different values of vibrator current may be obtained. Even if the current in the water return is not shunted through the oscillograph it is being drawn from the line to ground. It is easily seen why the water must be kept circulating when the power dissipated is figured. For example: at 220 000 volts and 0.1 ampere the resistance is 2 200 000 ohms and the power transformed into heat in the water is 22 kilowatts. With the sensitive vibrator this loss would be but one-fifth as much as with the standard vibrator. In any case a protective shunt should be used across the vibrator, as shown.

[2]See the JOURNAL for September 1927, Fig. 7, p. 458.

THOUSAND-AMPERE, ADJUSTABLE NON-INDUCTIVE SHUNT

For direct-current investigations a shunt must be used which will carry the main-line current. Fig. 6 shows an adjustable shunt which gives the proper drop to operate standard or sensitive vibrators at currents from 20 to 1000 amperes continues operation, and will stand as high as 25 000 amperes momentarily, provided this current is cut off instantly by a quick-acting circuit breaker. This shunt has the same drop at 20 amperes with its five strips in series as it has at 500 amperes with its five strips in parallel. This drop is sufficient to operate the standard vibrator on direct current. If the sensitive vibrator is used it should be placed in series with an adjustable low resistance so as to obtain the desired deflection. For momentary currents above 1000 amperes, even the standard vibrator should have a series resistance to limit the deflection. For 25 000 amperes (momentary) this should be of the order of 20 ohms for the standard vibrator or 100 ohms for the sensitive vibrator. An adjustable resistor with a range from 0 to 50 ohms is usually adequate, such as the four low resistors in the standard 20 200 ohm resistor unit, or the rheostat units for the 7th, 8th and 9th galvanometer elements.

The resistance of city water ranges from about 500 to 5000 ohms per inch cube, the average being about 2000. A single rubber hose of 0.5 sq. inch cross section would have about 4000 ohms per inch or 50 000 ohms per foot length. Thus, with 50 000 volts supply, and 500 000 ohms desired, 10 feet of hose single or 40 feet total, with return, would be needed.

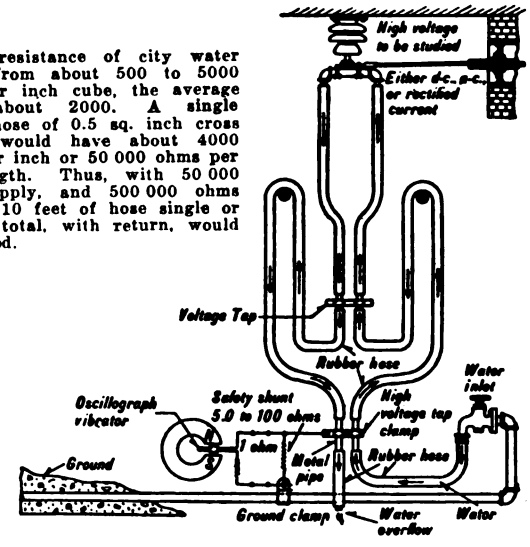


FIG. 5—HIGH-VOLTAGE RESISTOR OF THE CIRCULATING-WATER TYPE

This variable shunt is valuable in general testing of direct-current switches and circuit breakers, and is particularly valuable in electric car tests. As seen in Fig. 6 this shunt has five non-inductive strips which

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can be readily changed from a series to a parallel (or series parallel) arrangement by merely tightening the proper wing nuts on the bus-bar structure. It may also be re-connected for use as five separate shunts with 200 ampere capacity each, provided there is not much potential difference between any of the strips.

Thus this one shunt covers the range from slightly above 0.01 ohm to approximately 0.0005 ohm. The exact value of the resistance is of little importance because the oscillograph should be calibrated as a whole. Often it is impracticable to calibrate with the maximum current which is to be used in the staged test. If the sensitivity of the outfit is found with but one strip used in the shunt and with zero setting of the resistance dial switch, then:—

$$C = (c/r)(r+R)(P/S) \text{ approximately.}$$

where $C$ = sensitivity of unit in amperes (line) per each inch of deflection on the ground glass or film.
$R$ = resistance setting on dial.
$r$ = resistance of whole element circuit including leads, fuse, etc. when $R = 0$.
$P$ = number of strips in parallel.
$S$ = number of strips in series.
$c$ = current in amperes per inch deflection when $P = 1$, $S = 1$ and $R = 0$.

Actually when $r = 1.5$ ohm, $c = 70$ very approximately.
Thus when $P = 5$, $S = 1$, $r = 1.5$, $R = 25$.
$C = (70/1.5)(1.5+25.0)(5/1) = 6170$ amperes per inch deflection.
Thus if the maximum deflection was 2¾ inches the maximum current was approximately 17 000 amperes.

### ARRANGEMENT OF SWITCHES FOR TESTING

When a number of tests are to be made in a short time it usually pays to arrange a number of single-pole double-throw switches and possibly three double-pole double-throw switches, so that the oscillograph vibrators may be thrown from one test circuit to another.

A double-pole three-element switch panel is available which will fit in the top opening of the

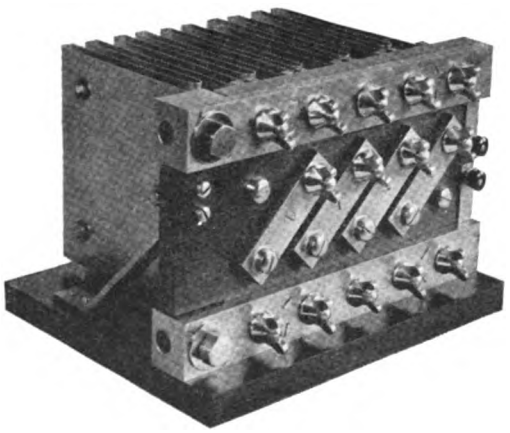

FIG. 6—ADJUSTABLE, NON-INDUCTIVE SHUNT
For continuous currents of from 20 to 1000 amperes.

multi-element oscillograph when no 7th, 8th or 9th elements or their resistors are used. This will throw any one of three vertical elements into the low resistance (0-50 ohms) or the high resistance (0-5000 ohms) control circuits of the 20 200 ohm, 8-dial, resistor unit. This arrangement is very convenient for a three-element oscillograph but will not control more than three elements. However two more elements can be used with one connected to the spare high resistor and the other to the spare low resistor, through holes in the upper rear wall of the oscillograph. If more than five galvanometer elements are used there will be little need for the double-pole three-element switch panel.

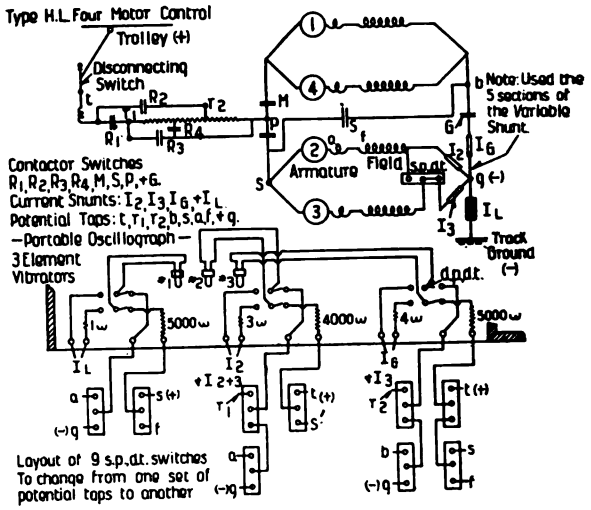


FIG. 7—DIAGRAM OF CIRCUITS FOR TESTING MULTIPLE-UNIT CONTROL, ETC. ON MOVING CAR

The work to be divided in the following classes:
Switching: Characteristics; Arc Division between various Switches.
Reversing: Reverse and Loop; Braking on Loop; Reversing with Power.
Transition: "Series-Parallel" to "Parallel" connection of Motors.
Acceleration: Per Step; Complete Cycle.

The #1 vibrator element was used to show the following:
E.m.f. of #2 armature .....Potential Taps *s* to *a*
E.m.f. across the "S" Contactor (#2 motor) .....
.....Potential Taps.....*s* to *g*
E.m.f. across the #2 compensating field .....
.....Potential Taps.....*f* to *a*
E.m.f. across the #2 main series field .....
.....Potential Taps.....*f* to *g*
Current in line .....Shunt.....$I_L$

The #2 vibrator element was used to show the following:
E.m.f. across "$R_1$" Contactor ..Potential Taps..*t* to $r_1$
E.m.f. from trolley to ground ..Potential Taps..*t* to *g*
E.m.f. across #2 armature ...Potential Taps...*s* to *a*
Current in the #2 motor circuit.....Shunt.....$I_2$
Current in #2 and #3 motor section...Shunt...$I_2+3$

The #3 vibrator element was used to show the following:
E.m.f. across #2 compensating field.....
.....Potential Taps.....*f* to *g*
E.m.f. across "$R_2$" contactor...Potential Taps...*t* to $r_2$
E.m.f. across the "S" circuit breaker .....
.....Potential Taps.....*s* to *b*
Current in "G" switch.....Shunt.....$I_6$
Current in #3 motor.....Shunt.....$I_3$

A very convenient layout is shown in Fig. 7, using the three double-pole, double-throw switches of the three-element switch-panel and also nine single-pole, double-throw knife switches. This arrangement made it possible to take more than forty oscillograms of transient conditions on a multiple-unit-control train of several cars, while this train was rushing over a regular route through the thick of traffic, without a single failure. The variable shunt is used in this arrangement as three 200-ampere shunts and one 400-ampere shunt, with one point common for the four circuits. A whole series of tests was made in less

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than half a day, without leveloping a single film. This could not have been done if the test had not been carefully planned and a suitable switching arrangement used. The tabulation below the figure shows the different characteristics to be recorded. The action of each motor, each switch, each armature, main field, compensating field, etc. was recorded, also the action of the reverser and each notch on the controller was studied.

### PHOTOGRAPHIC SHUTTER AND REMOTE-CONTROL MECHANISM

The multi-element oscillograph photographs transients as easily as most other oscillographs photograph recurrent phenomena. Fig. 8 shows the driving head attached to the shutter-mechanism side of the optical box. The cross-arm mechanism on the driving head opens the mechanical shutter during just one revolution of the photographic drum. In this illustration the viewing mirrors are in place on the face of the optical box and the mechanical shutter is propped open by an arm extending forward from the base of the trip magnet. Thus the viewing mirrors are operated through the driving head while the shutter is kept open. Ratios from 1 to 1 up to 7 to 1 may be obtained with the driving head and 6-volt motor pulleys. The polygon of four mirrors should be driven at a speed of 300 or 450 r.p.m. to observe 60-cycle alternating-current waves. The steps on the pulleys, and the motor-field rheostat (on the lower front of the oscillograph) enables the operator to drive the viewing mirror at any desired speed. By supplying the motor armature at two, four and six volts, from a three-cell lead-plate storage battery, it is possible to vary the speed of the driving head from 40 to 1200 r.p.m. for photographic purposes. This represents a total exposure of from one second to approximately 0.03 second for a 10-inch effective length of film.

The photographic shutter is set as follows; first the operator releases the telescoping finger by slightly drawing out the tip of the arrow-headed flat spring on the very end of the shutter head, see Fig. 8. This finger is forced out, by an internal helical spring until it is about ⅛ inch longer than the fixed-length finger, which is shown 90° from the movable finger. The shutter head is then grasped by the operator's thumb and forefinger and is pulled out (about ¼ inch) and is rotated clockwise until the elongated finger can be inserted under the catch on the trip-magnet arm. The shutter prop, which was used to hold the shutter open during viewing, must be moved down out of the way so that it will not interfere with the later action of the shutter.

The complete photographic action can be better understood by reference to the earlier description and illustrations appearing under the heading "The Optical Box"[3]. The action of the shutter can be best understood by reference to Fig. 8. When the shutter is properly set, and the film holder is operating at the desired speed, the operator merely moves the lamp-control switch to the 3-volt position and pauses there an instant to permit the lamp to come up to normal brilliancy. He then throws the switch to the right against a stop which has been set for the desired abnormal voltage. This stop is electrically connected to the tripping magnet through an adjustable contact on the driving head, so that the shutter is released by the magnet and the shorter finger drops a slight amount onto the cross-arm which is worked back and forth by the driving head. This cross arm releases the shorter finger during the inactive third of the revolution of the photographic drum, when no film is opposite the optical slot. Thus the shutter, by the action of its spiral spring, snaps through an angle of 90 degrees

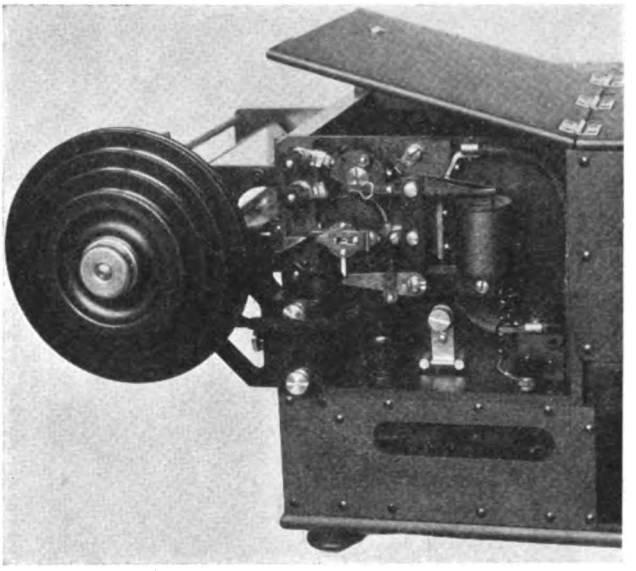

FIG. 8—DRIVING HEAD, SHUTTER MECHANISM, REMOTE CONTROL, AND CUT-OUT SWITCHES

to its open position. When the forward edge of the revolving film reaches the focal line of the oscillating beams of light the actual exposure begins. Two-thirds of a revolution (10 inches) of active film is thus exposed. Meanwhile the cross-arm has traveled in towards the shutter head and has forced in the telescoping finger so that the arrow-headed spring may hold this finger in its inward position, where it is the same length as the other finger. Hence exactly one revolution after the cross-arm releases the shorter finger to open the shutter, it releases the telescoping finger and thereby closes the shutter. In this way the shutter is open during just one revolution of the photographic drum and its snapping action occurs during the inactive third of the revolution. In addition, the shutter knocks

[3]See Oscillography—VI in the JOURNAL, for November 1927, p. 560; in the first chapter of the multi-element oscillograph.

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open the cut-out switch when the shutter closes. This extinguishes the lamp. All of this action takes place so quickly that the human eye cannot see the shutter move. The operations are actually so simple that an operator often takes a series of five exposures, shifting the film between each exposure, with a total time between each exposure of but 15 seconds, or five shots in one minute.

### TRANSIENT CONTROL

This rapid operation may be achieved when controlling transients. The only additional feature which must be taken care of is the remote-control switch, and the proper setting of the adjustable contact on the driving head. The single-pole, double-throw remote-control switch is shown in Fig. 8, at the upper front corner of the optical box. This is held in one position by another arm on the tripping-magnet armature. A spiral spring between the

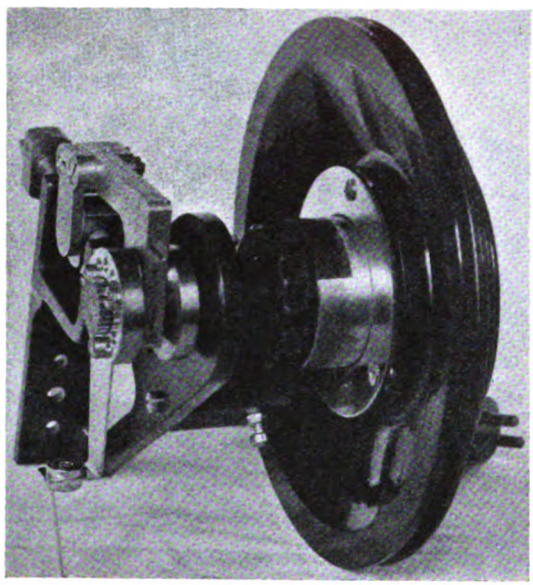

FIG. 9—DRIVING HEAD UNIT

switch and the case causes the switch to snap to the other position when released by the action of the tripping magnet. In actual operation, the remote-control switch should be connected into the proper control circuit of the device to be studied. Usually this is a contactor which directly closes or opens the electrical circuit being studied, or closes or opens the control circuits of very large apparatus, such as oil-filled circuit breakers, etc. The adjustable contact on the driving head, Fig. 9, should be set so that the remote-control switch will be released after a definite part of the revolution of the driving head which is equal in time to the time lag of the remote-control lead apparatus. The action of this snap switch may be ¾ revolution of the photographic drum ahead of the opening of the shutter, or even slightly more than one revolution before the start of the exposure of the film. Thus if the total time delay between the snapping of the control switch and the actual start of the power transient is one-half second, the film drum may be rotating as fast as 120 r.p.m., giving a total exposure of but 0.33 second (or twenty cycles of a 60-cycle supply) on the 10-inch length of film. With this method the start of the transient can be located within less than an inch of the desired position on the film. When the remote-controlled device is a standard contactor its action may be in the order of 0.1 second. Then the film may be driven at a maximum speed of 600 r.p.m. and give a 10-inch record in 0.067 second. If the transient condition lasts for more than 0.05 second the drum speed may be reduced and the contact on the driving head shifted so as to operate the tripping magnet later in the revolution. In all cases the actual opening of the shutter is done by the cross arm and not by the tripping magnet. The part of the revolution where the shutter opens is determined by the setting of the arm between the driving head and the film holder. This arm has twelve possible settings, but is usually placed so as to cause the shutter to open one-fourth revolution before the beginning of the film is presented to the optical slot. Only for very slow film speeds is it ever necessary to reduce this from one-fourth to one-twelfth or to zero lead. For very slow film speeds, it is even possible to set the contact and driving arm on the driving head, so that the shutter snaps clear of the cross-head at the same instant that the remote-control switch functions. This arrangement has been used to start a five-car train on its complete cycle of acceleration. The remote-control switch may operate the train controller directly or merely light a lamp in front of the motorman so that he may start notching up immediately. Even moderately high-speed films may be taken of transients started by the motorman, or station attendant, provided the personal equation of lag is determined for that man. Furthermore, all this adjustment may be determined without taking a single film, if the operator will view the light beams on the ground glass, of the viewing attachment, and repeat the test and shift the contact on the driving head, until it is seen that the current wave is momentarily zero just when the shutter snaps open. Then the contact lead should be reduced equal to the lead in the action of the shutter over the start of the actual exposure.

An operator once familiar with this method may take hundreds of films without developing any to see if the desired transient is being obtained. This method is very flexible and very reliable, and often enables the operator to obtain better records on a ten-inch length of film than he could obtain on a five-foot film with older methods of control.

### SIMULTANEOUS VIEWING AND PHOTOGRAPHING

The action of simultaneous viewing and photographing is more easily understood, now that the

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shutter action has been explained. The oscillograph is arranged with six sets of beams striking the six vibrator mirrors of the galvanometers and these beams are reflected straight forward, on the level with the mirrors, to the focal plane shutter (consisting of two concentric tubes with two opposite longitudinal slots in each). Thus these beams are inactive until the shutter is opened later. Three more beams of light come from the reflecting prisms, through the adjustable slots (the 7th, 8th and 9th slots being moved out of line with the others) and onto three of the six vibrator mirrors, and are thence reflected toward the front and slightly upward so that they are caught by the reflecting prism of the simultaneous-viewing attachment. They are thence passed through the extra cylindrical condensing lens and are focused as three spots of light on the ground glass of the viewing attachment above. When alternating or other currents pass through these vibrators, the spots of light are seen to dance on the ground glass. When the polygon of mirrors is rotated, the observer sees waves of light giving visual impressions of the varying currents in the three vibrators. Meanwhile the film drum has been rotating at the desired speed and the lamp has been on normal voltage. When the desired intensity of oscillations is observed, the operator merely changes the lamp control switch to the abnormal voltage position and against the stop which causes the tripping magnet to release the shutter. One revolution of light exposure is then admitted to the drum and the 10 inches of active film receives the desired photographic impressions. The observer continues to see the waves, at increased brilliancy, until the shutter closes and extinguishes the lamp. Then the drum may be stopped, the film turned to the next setting, the shutter reset and the lamp lighted at normal voltage, so that visualization may continue until the next desired transient appears. Each record may be taken at a film speed as high as 10 inches in 0.03 second.

Simultaneous photographing may also be carried out with the long film holder so as to take many repeated tests and have each test last as long as desired. In this case the remote control switch is placed in the six-volt motor circuit and the shutter prop is set so that the shutter cannot close, even after it snaps open. The operator then merely throws abnormal voltage onto the lamp when he sees the desired transient building up in the viewing mirrors. The motor then starts the film immediately and the exposure continues until the operator reduces the lamp voltage and resets the shutter and the remote-control switch. This stops the exposure but not the waves in the viewing attachment. An 8-foot film will operate for a total of nearly two minutes and yet show up any individual cycle of a 60 cycle wave which is greater or less than the proceeding cycle. For these very slow speeds it is necessary to use a pulley-and-gear-reduction unit between the motor and the oscillograph driving head.

### GEAR REDUCTION UNIT

In Fig. 10 is shown a unit which will give a very great range of speeds for any photographic attachment when driven with any motor. This unit has a three-inch diameter driven pulley connected to a shaft having two pinions. Either of these pinions may be meshed with the large annular gear on the driver-pulley shaft, so as to give a gear reduction of 24 to 1 or 8 to 1, according to the setting. It is well known that an annular gear gives much better action than a spur gear when uniform velocities are essential. The minimum diameter pulley step of the driver is ¾ inch, hence the greatest ratios provide a reduction of $4 \times 24 \times 7$ or 672 to 1 between the six-volt motor shaft and the driving head of the oscillograph. When the long film holder is used, an additional 3 to 1 reduction takes place in the gearing in that the total reduction is 2016 to 1. Now since the 6-volt motor will run reliably at 800 r.p.m. (fairly well even at 400 r.p.m.) and since one revolution of the drum on the long film holder means exactly one foot of film, the film may be driven as slow as 800/2000 = 0.4 foot per minute or 0.08 inch per second or 12.5 seconds per inch, or 20 minutes for 8 feet.

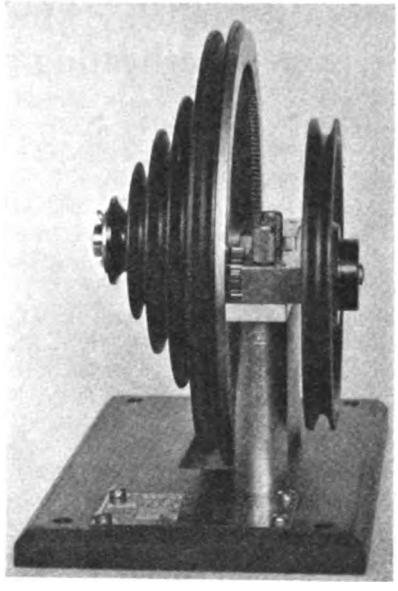

FIG. 10—PULLEY AND GEAR REDUCTION UNIT
For use between the motor and film holder for obtaining slow-speed records.

Since nine simultaneous records can be made on the one 6.5 inch width of film, and since this film can be driven very slowly, it should be feasible to set this outfit so that it would operate every time any switching is done on a three-phase power system. In other words, the initiating relay could be set to operate from the current in the neutral or as

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a function of this and any other currents, such as direct-current control current, etc., so that the oscillograph would start operation at the least provocation, and continue to operate for five seconds, or until each current had returned to normal value.

The various pieces of apparatus described are not all necessary for any one application. However the design of the multi-element oscillograph permits a large selection of parts and covers an extremely broad field of applications.

## Protecting Railway Motors from Overheating

A NOVEL, yet surprisingly simple, method of indicating the temperature of electric locomotive motors to the engineman has been developed and applied. This scheme does not employ thermo-couples or search coils, as have previous schemes, but depends upon another well-known electrical device—the Wheatstone bridge—and upon the fact that the resistance of the motor field windings increases directly with the temperature.

This method is shown schematically in Fig. 1. A shunt *A*, a fixed resistance *B* and resistance *R* form the three known sides of the bridge. Resistance *R* is made adjustable to permit calibration of the bridge. The series field of one of the traction motors, which forms the unknown side of the bridge, is connected in series with the shunt. A center-zero millivoltmeter is connected to the inside terminal of the shunt and to the common terminal of the known resistances.

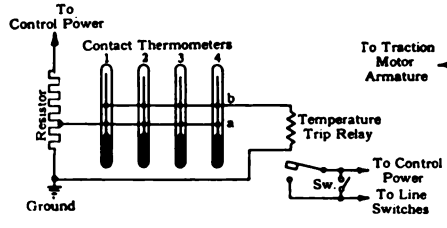


FIG. 2—OVERTEMPERATURE PROTECTION

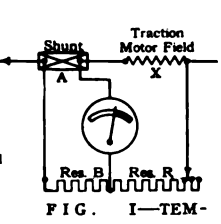


FIG. 1—TEMPERATURE INDICATION

The bridge is so calibrated that when the motor is at rated, full-load temperature no current flows through the meter and the pointer stands almost vertical. Should, however, a sustained over-load occur, the resistance of the field will increase, more current flows through resistance *R* and through the meter than through resistance *B*, causing the pointer to deflect to the right into the reddened portion of the ammeter scale indicating the danger. The hotter the motor gets the further the pointer moves into the red, thus informing the engineman not only that the motors are overheated but the relative extent of the overheating.

Should the motors reach a dangerously high temperature and the engineman fail to reduce the load on the motors, another device acts automatically to shut off the power supply to the motors. This device, shown diagramatically in Fig. 2, is as simple as the temperature indicators.

A mercury thermometer is permanently placed in a cell extending through the frame of each motor into the field coil. Into the walls of the thermometer are fused two contacts as *a* and *b*. A lead is fastened to each of these contacts and carried to the engineman's control. The lower lead *a* is connected to a source of potential, as a section of the controller resistance. The other lead is connected to a relay to ground.

If a motor should get dangerously hot, the mercury in the thermometer would rise and short-circuit contacts *a* and *b*. The circuit from the trolley to ground through the relay is then complete. The energizing of the relay opens a set of contacts which disrupts the flow of power to the motors.

Under some conditions, it might be desirable to operate the locomotive even at the risk of burning out a motor. The engineman can, by breaking a seal and closing a switch which short-circuits the temperature trip relay, restore power to the motors. The seal being broken is a record of the fact that the temperature relay has operated and the switch been closed. The engineman thus must give account to his superiors for such action.

## The Why of the Equalizer

HOW to obtain a pull is usually more of a problem than how to get rid of it. However, this is not always the case. The magnetic pull that may be exerted by one side of the field in a large, direct-current armature, out of center by a small fraction of an inch, may become as great as several tons. To make matters worse, such a condition tends to be cumulative and results in the heating and rapid wearing of the bearings, to say nothing of bending the shaft and rubbing the armature.

It is impossible to build a perfect mechanically symmetrical armature and rotor, and there are slight differences in the magnetic paths, causing the fluxes from the poles to differ. Thus, the voltage induced in the parallel circuits of lap-wound armatures as they pass under one pole will be different from that induced in them as they pass under the next pole. This difference in potential causes a current to circulate in the armature coils and brushes of similar polarity. It is these circulating currents which cause the unbalanced magnetic forces, and which, in addition, make such a nuisance of themselves in other ways: overload the brushes, add to the heating, and cause sparking at the commutator.

Armature cross-connections serve as the remedy. Unlike many cures, they get at the cause of the trouble, i.e., unequal field pole fluxes. When there is a potential difference between two armature coil supposedly equal, current flows in the cross-connections between them. These currents set up magnetic fields which magnetize the poles deficient in flux strength

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and demagnetize those whose flux is too great. Thus a balance is automatically obtained.

Since these cross-connecting currents tend to eliminate the unbalance that causes them, the actual currents that flow are small. The resistance of the cross-connections is very low, as heavy copper and soldered joints are used. The heating in them then, is small—insignificant when compared to the heating loss they prevent.

Wave-wound armatures do not experience the detrimental effects obtained on a parallel-wound armature not cross-connected. This is primarily because any lack of uniformity in the poles is automatically averaged. Equalizer connections, therefore, are not used on the wave-wound armature.

# The Reason for Chorded Windings

L. R. LUDWIG

IN his studies of the direct-current machine, Mr. B. G. Lamme, found that a winding both sides of which did not fall under the corresponding point of adjacent poles was an aid to commutation. Consequently, he patented the short-pitch winding, whose advantages have accorded it universal application in all types of rotating electrical machines. Its one real disadvantage is the lowering of the voltage which can be generated or the magnetomotive force which can be established, as compared to that of the full-pitch winding.

One of the principal advantages of the short-pitch winding, which has extended its use to alternator design, is the elimination of harmonics from the voltage wave. Since the fundamentals of the voltage generated in the two sides of a coil are out of phase by an angle whose sine is half the angle of the chord, the *nth* harmonic generated is out of phase with the corresponding harmonic in the opposite coil side by $n$ times the angle. Hence to eliminate the harmonic $n$, it is only necessary to make the pitch factor, $k = sin \frac{nr}{2}$ for that harmonic to equal zero. The pitch factor is $k$, and $r$ is the pitch of the winding in electrical degrees. To make $k = O$, it is necessary that $r = \frac{2\pi q}{n}$, where $q$ is any integer. From this it follows that a 2/5, 4/5, 6/5, etc. pitch will eliminate the fifth harmonic. Nor does the advantage stop with the elimination of a single harmonic, for the other harmonics are reduced by a greater percentage than the fundamental, since their out-of-phase angle will be greater.

A wave form of flux set up by a chorded winding in an induction or synchronous motor will be more nearly a sine wave on account of the elimination of harmonics in the same way. Chording the winding, therefore, is equivalent to distributing it in a greater number of slots per pole. The m. m. f. of a distributed three-phase winding on an induction motor, for full pitch and various percentages of chording, is shown in Fig. 1. The motor has 36 slots per pair of poles and contains a lap winding having two coil sides in a slot. The full-pitch wave form is triangular at the instant, shown in Fig. 1, when the current in one phase is a maximum. As the current changes magnitude with time, the wave form changes into a trapezoid, and again into a triangle. However, the point to be made in regard to chording the winding is the elimination of harmonics, and since this can be illustrated regardless of the point of time chosen, the instantaneous time at which the current is a maximum in one phase is chosen. The wave form becomes trapezoidal when chorded, and closely approaches a sine wave when the pitch is 83 percent. At this pitch half of one phase overlaps half of the adjacent phase. As the winding is chorded further, the harmonics begin to reappear, and the wave form reverts to its triangular shape.

The actual wave form has a number of small harmonics which exist on account of the imperfect distribution of the copper about the armature periphery and which give it a "stair-step" rise. In the curves as plotted, straight lines of average value were drawn through the stair-steps. The sharp corners are actually rounded, but exist on account of the assumption that the magnetomotive force increases instantaneously as a conductor is passed.

Another reason for the use of chorded windings, as previously stated, is the improvement in commutation. If the winding be chorded one slot, the slot flux, or that flux caused by the unequal m. m. f. of the teeth and which must be cut by a commutating coil, is halved. Since this flux is a large factor in producing sparking voltage in the coil, the sparking voltage is greatly reduced, and commutation is correspondingly improved. Further chording is not effective in reducing the slot flux, and adds the disadvantage that one coil side is thrown back under the main flux during commutation. As a result, direct-current machinery and converters are not ordinarily chorded more than one slot. Another disadvantage, more than offset with slight

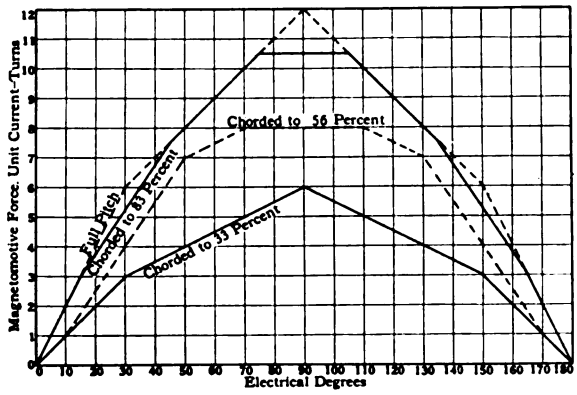


FIG. 1—THE CHANGE IN M. M. F. WAVE SHAPE AS THE WINDING IS CHORDED

chording, however, is that the width of the commutating pole face is unduly increased, due to the wider commutating zone, when the requisite space is often not available. Conversely, the armature m. m. f. is slightly decreased.

On single-phase commutator type motors for railway service in which there are four coils per slot, it has been found that chording the winding three-fourths of a slot throws more coils undergoing commutation simultaneously closer together in the slots than any other combination. The advantage of this close inductive coupling is that energies in the fields of the short-circuited coils are mutually destructive, and need not form an arc at the brushes for their dissipation. In practice, the commutators blacken less with the three-quarter slot chording than otherwise, which fact supports the above conclusion.

Despite the fact that a short-pitch winding develops a smaller e. m. f. than a full pitch, a saving in copper results from the shortening of the end connections. Consider an induction motor having 72 slots each containing two coil sides of five turns each. It has four poles and an effective diameter midway of the winding of 20 inches. The length of the armature is 15 in., the copper must project two inches beyond this before being bent, and the end turns make an angle of 45 degrees with the axis. Since this is a four pole motor, the distance from slot 1 to slot 19 corresponding to full pitch is 20 × cos 45 degrees

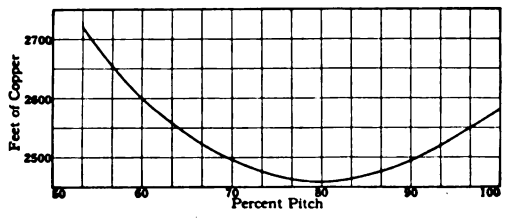


FIG. 2—THE VARIATION IN COPPER REQUIRED WITH CHORDING

= 14.1 inches. The slanting part of the end turns is however at 45 degrees to this distance and hence its length is 14.1 ÷ cos 45 degrees = 20 inches. At the extreme end the mean length of the bend is 4 inches. Hence the mean total length of turn is,—

$$2\,[15 + 2\,(2) + 20 + 4] = 86$$

There are 5 × 72 or 360 turns, or $\frac{360 \times 86}{12}$ = 2580 feet of copper required for full pitch. If the winding is chorded to 80 percent the end turns will be shortened according to the decreased distance between coil sides, and the mean length of turn will become 78 inches. To generate the same voltage, more turns must be used. If the air-

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gap flux is sinusoidal, the voltage generated by a fractional pitch winding will be,—

$$E = E_1 \sin \frac{r}{2} \quad \text{.....(1)}$$

where $E_1$ is the voltage of the full-pitch winding, and $r$ is the pitch of the winding used, expressed in electrical degrees. $\frac{E}{E_1}$ is called the chord factor and for the 80 percent pitch winding would equal,—

$$\sin \frac{0.8 \times 180}{2} = 0.95$$

The total feet of copper used in the above winding of 80 percent pitch must therefore be,—

$$2580 \times \frac{78}{86} \times \frac{1}{0.95} = 2460 \text{ feet}$$

resulting in a saving of 4.65 percent.* This saving in copper means less $I^2R$ loss and higher efficiency. As the pitch decreases, the voltage, dropping off along the sine curve, decreases faster than the copper saving in the end turns; so that more copper would be required than with a full pitch winding, should the pitch be 80 percent or less. A curve between feet of copper required and percent pitch is plotted for this particular machine in Fig. 2. Equation (1) is derived from adding by means of Fourier series voltages which are out of phase. It may be in error a few percent if the flux wave is triangular or rectangular.

In the design of a rotating machine, frequently the values of air-gap flux and speed are established so that the required voltage is not generated. In this case fractional pitch windings lend flexibility to the designer by allowing him to design the machine for slightly greater voltage than rated, then reduce it by chording the winding a sufficient amount. It is thus contributory to the use of standard frames where the number of slots is the same in many types of machines.

Tooth pulsation looses, which become considerable in some machines where the frequency of flux changes in the teeth is high, are somewhat reduced by chording the winding. This results from the coil sides of different phases occurring in the same slots, and lessening the total slot flux, since the currents in the two coil sides are out of phase. In the same way the mutual inductance between coil sides is reduced and the reactance of the winding therefore lowered. The reactance is further reduced by the shorter end connections, the number of these remaining the same regardless of chording. In an induction motor, the lower reactance means a lower magnetizing current. Induction motor losses are further decreased by elimination of harmonics in the air-gap flux. The harmonics also cause reverse torques of 15 to 20 percent in the motor, which disappear with the elimination of the harmonics. Chording is common in induction and synchronous motors. Percentages up to 33 are used in alternators, and commutator machines are chorded up to 5 percent.

*This statement is correct in principle, but generally is somewhat modified by the fact that the number of turns must bear certain fixed relations to the number of poles, number of phases and number of slots.

# RAILWAY OPERATING DATA

THE ELECTRIC JOURNAL

January 1928

The purpose of this section is to present accepted practical methods used by operating companies throughout the country.

The co-operation of all those interested in operating and maintaining railway equipment is invited. Address R. O. D. Editor

## Snow Removal Equipment

A few years ago in one section of the country during the severe winter storms, the street railway companies had about one-third of their motor armatures fail in service. Considerable of this trouble could have been avoided if all of these properties had been provided with the necessary snow fighting equipment, in the absence of which the cars were used to fight the snow, with disastrous results. The apparatus as outlined here in detail should be considered as a part of the necessary equipment for snow fighting.

### SWEEPERS

The sweepers are the first equipment called into service to fight the snow, and are usually kept in continuous operation until the tracks are clear. Snow sweepers consist of either a single or double truck car, self-propelled, fitted with a rotating broom at either one or both ends. These are standard equipments on a large number of street railway lines in United States and Canada.

A large number of special types of sweepers and combination sweepers and plows have been developed and are being used by railway operators to meet special local operating conditions. Some of these special types are:—

a—Double-truck open summer passenger cars fitted at one end with a rotating broom.

b—Double truck freight box car fitted with a plow at the front end and a rotating broom under the center of the car.

### PLOWS

Snow plows are required to clear the tracks when the snow becomes too heavy for the sweepers. Snow plows consist primarily of self-propelled or pushed cars, with four or eight wheels fitted at the front end with a metal or wooden shaped nose which forces the snow from the track. They are named as follows:—

*a—Nose Plow*—Where the tip or point of the plow is in line with the center of the track. These are mostly self-propelled and used to clear the snow from single tracks.

*b—Shear Plow*—where the tip or point of the plow is off-set from the center of the track. These are mostly self-propelled and used to clear the snow from double track lines.

*c—Push Plow*—a special build of car with either a nose or shear type of plow attached to the front end. This car is pushed by a separate motor-driven unit.

*d—Pilot Plow*—is a detachable plow attached to the front end of an interurban passenger or freight car.

*e—Wing Plow*—the adjustable arm attached to the side of any plow or sweeper used to widen the cut.

When the snow conditions are unusually severe, the rotary plow has been used to a good advantage in cleaning the tracks. This type of machine consists of either a single or double truck, specially built car with a large motor driven fan located at either one or both ends. A rotary plow as used by one operator is as follows:—

Single truck construction.
Double end operation.
Total weight 12 ton.
Two 25 hp motors used to drive the car.
Two 35 hp motors used to drive the fans, one at each end of the car.

The rotary plow is only of value where the volume of snow is so large that it cannot be readily handled by the use of snow plows. Generally speaking, very few of the railway operators have found it worth while to add rotary plows to their snow fighting equipment.

### ICE CUTTERS

A number of operators have designed and built special machines to cut away the snow and ice packed down between the tracks by automobile traffic after a heavy snow storm. These machines are usually home-made and naturally in line with the ideas of the various master mechanics who have built them, which in general are as follows:—

a—A rigidly braced horizontal bar about 10 ft. long fitted with a number of sharp cutters. This bar is mounted between

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# *Lubrication* as viewed by those who build your equipment

## Chapter I

### *What they know*

No one knows better than the manufacturer of mechanical equipment that exactly suitable oils should be used in the units he carefully designs and builds. He cannot, of course, dictate to his customers what oil to use. Once his machinery goes into service its efficient lubrication is in other hands. He can only make recommendations based on sure knowledge.

There are 417 major manufacturers of industrial machinery in this country. The great majority of them recommend the use of specific lubricants produced by the Vacuum Oil Company.

The following statements are quoted from lubrication bulletins which the machinery builders send out with their units.

## Chapter II

### *"Correct lubrication for our equipment"*

**Maker of Oil Engines:** "We have cooperated with the Vacuum Oil Company, recognized authorities on the subject of correct lubrication, to determine the most suitable oils for our engines."

**Maker of Gas Engines:** "To guard against operating difficulties which might arise through the use of incorrect oils we offer our customers Gargoyle Lubricating Oils."

**Maker of Steam Turbines:** "After exhaustive tests on our equipment operating under service conditions, we recommend the high-grade lubricants marketed by the Vacuum Oil Company."

**Maker of Steam Engines:** "Vacuum Oil Company lubricants are selected because actual field results have shown them to be uniform and high-grade in quality."

**Maker of Steam Turbines:** "Years of successful experience have convinced us that Gargoyle lubricants admirably meet the requirements of this service."

## Chapter III

### *A good example to follow*

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the wheels on a special truck which must be pushed over the road.

b—A cutting bar similar to the above which is attached to the front of a snow plow, as shown in Fig. 1. This unit is self-propelled.

c—A cutting bar similar to the above which is mounted under the center of a special box car. This unit is pushed by a locomotive.

d—A hinged type special cutter attached to the front truck of a standard car, as shown in Fig. 2. This unit is self-propelled.

e—A special motor-driven rotating cutter, spring supported and mounted beneath the car as shown in Fig 3. The cutter is driven by a 50 hp motor while the car is propelled by four 50 hp motors.

### MISCELLANEOUS EQUIPMENT

There are a number of smaller details which have been found to be very helpful to the operators who are confronted by bad snow conditions. Some of these are as follows:—

*a—Sleet Cutters for the Trolley*—These are specially designed sleet wheels to replace the standard trolly wheel to cut the ice from the wire. Some use a sleet scrapper which is attached to the harp without removing the standard trolley wheel. Another device sometimes used is a special sliding

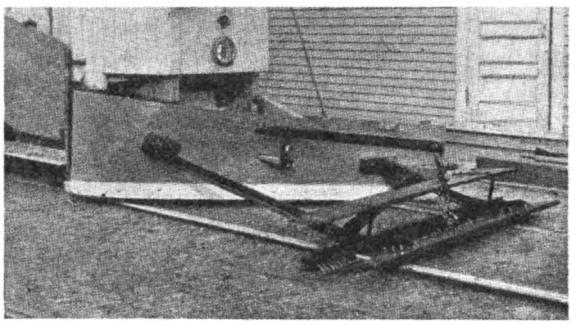

FIG. 1—AN ICE CUTTER MOUNTED AHEAD OF THE SNOW PLOW

shoe acting like a pneumatic riveter in that it strikes the sleet covered trolley wire with rapid hammer blows which loosens the ice on the wire.

*b—Steel Cutters for Third Rail*—Hardened steel scrapers mounted in front of the lead wheels on the car are forced down on the sleet covered third rail by a heavy spring pressure. Stiff steel wire brushes are sometimes used to keep the third rail clean.

*c—Snow Scrapers*—Cars which are fitted with steel scrapers that can be dropped down on the rails at the front of the car to clean the snow from the tracks.

*d—Snow Fences*—Fences are erected along the right of way, especially for interurban service, to prevent the snow from forming in drifts on the car tracks.

*e—Snow Melters*—A recent development used on the elevated and the subway tracks is the electric-heated track switch. These so called electric snow melters, placed at the important points of a switch, provide a simple means of keeping it clear, thus avoiding train delays and sometimes derailments and wrecks, due to frozen switches.

### REMOVING SNOW FROM THE STREETS

The charters of some railway companies require that they help to remove the snow from some of the streets. With a number of operators, this work is now very urgent since a great many companies now operate bus lines on many of the streets. Until recently this work was done by means of teams and flat cars, but at present, it is handled by a variety of equipment somewhat as follows:—

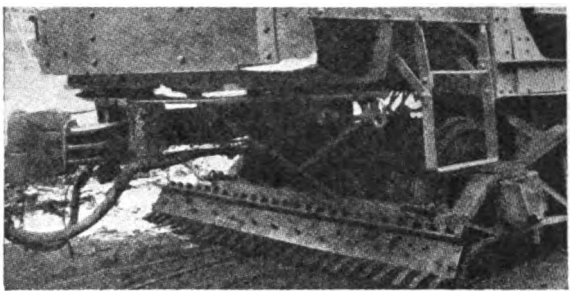

FIG. 2—A HINGED ICE CUTTER

a—Motor busses fitted with plows.
b—Tractor engine fitted with a rotating broom.
c—Caterpillar tractor fitted with a small rotary plow.
d—Various types of snow loaders.
e—Motor trucks to haul the snow.
f—The use of sewers to receive the snow.

From the experience of a number of operators, the following are some of the important things to be considered in connection with this subject:—

a—Keep an eye on the weather reports.
b—Get busy as soon as the first flake of snow falls.
c—Keep all switches clear of snow and ice, to prevent derailments.
d—Have on hand a good supply of sand and salt.
e—Keep the equipment in good operating condition.

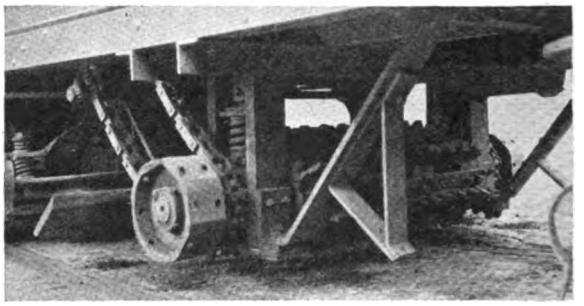

FIG. 3—A ROTATING ICE CUTTER

f—Use trained crews, skilled in the operation of the snow fighting equipment.
g—Have a snow fighting organization available.
h—Follow a definite plan of attack.
i—Do not use passenger cars to buck the snow.

JOHN S. DEAN.

# The JOURNAL QUESTION BOX

Our subscribers are invited to use this department as a means of securing authentic information on electrical and mechanical subjects. Questions concerning general engineering theory or practice and questions regarding apparatus or materials desired for particular needs will be answered. Specific data regarding design or redesign of individual pieces of apparatus cannot be supplied through this department.

To receive prompt attention a self-addressed, stamped envelop should accompany each query. All data necessary for a complete understanding of the problem should be furnished. A personal reply is mailed to each questioner as soon as the necessary information is available; however, as each question is answered by an expert and checked by at least two others, a reasonable length of time should be allowed before expecting a reply.

2785—*CR* RELAY OPERATION—Fig. (a) is a diagram for the protection of two circuit breakers on a loop cable in one station. The substation circuit breaker is taken off between the two loop circuit breakers. The protection is for opening the cable without killing any station in the case of a fault. (1) What will cause a potential in the ground leads which will operate the ground relays and how would you suggest testing? (2) Is it correct for the main *CR* relay to close No. 1 trip contacts when No. 1 circuit breaker opens? Also when No. 2 circuit breaker opens should the relay contacts for No. 2 close?

R. L. G. (ONT.)

The scheme of connections in Fig. (a) is in error in several respects, so that a general analysis will be given of

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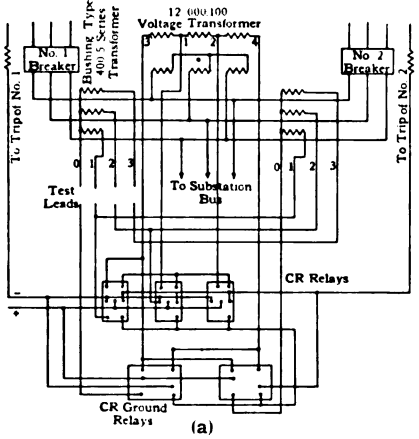
the complete relay problem. The errors in the diagram submitted are:—1—Phase two current connection is shown connected to trip circuit, which of course needs no explanation. 2—Phase three has no current connections to relay whatever. 3—Either potential or current connection of one ground relay should be reversed in order to give correct operation. 4—Potential connections are not the best and will give incorrect operation under certain conditions of fault. Fig. (b) is the recommended scheme of connections. The major differences are as follows:—1—Use is made of a set of auxiliary potential transformers. 2—Ground relays are connected differently. 3—125 volt relays with standard 30 degree connec-



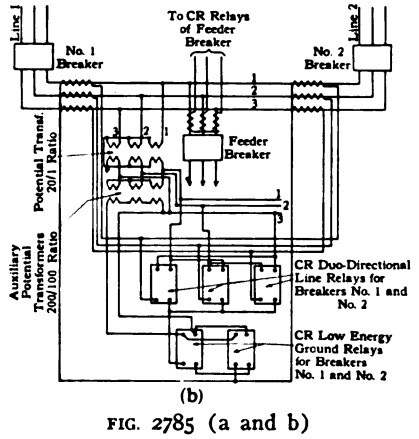


To CR Relays of Feeder Breaker
Line 1
Line 2
No. 1 Breaker
No. 2 Breaker
Potential Transf. 20/1 Ratio
Feeder Breaker
Auxiliary Potential Transformers 200/100 Ratio
CR Duo-Directional Line Relays for Breakers No. 1 and No. 2
CR Low Energy Ground Relays for Breakers No. 1 and No. 2
(b)

FIG. 2785 (a and b)

tions of voltage and current are used. It has been found by careful study and by the actual test that if ground relays are connected in the secondary delta of the main potential transformer and used together with 70 volt relays connected in star, that certain incorrect operations will result for combinations of line to ground and phase to phase short circuits. Investigation of the action of line relays show that certain extreme phase distortions occur which render their operation unreliable unless an auxiliary set of potential transformers is used together with 125 volt relays with standard 30 degree connections. The analysis is too lengthy and involved to be covered here. The ground relays are connected in Fig. (b) to get the total ground current and not part of it as shown in Fig. (a). The connections as originally submitted are correct if one current or one potential connection is slightly changed, as explained above, but are not as desirable as the scheme of connections shown in Fig. (b). A short circuit is usually of some lagging power factor so that if the voltage across a relay lags the current of the relay at 100 percent power-factor by an angle of 30 degrees it has been found to give very satisfactory results and should be used wherever possible. The connections of Fig. (a) show a zero degree relation between current and voltage which means that any lagging power-factor will tend to decrease the torque of the relay as the angle of lag increases. Connections shown in Fig. (b) are recommended for this installation. brief answer to question (1) can be given as follows:—Suppose that a ground occurs on phase 1 wire, Fig. (b). This is equivalent to a short circuit on the primary of transformer 1. This in effect, converts star-delta connection into an open-delta connection, therefore the unaffected transformers 2 and 3 tend to maintain the voltage across the relay. The open-delta voltages add up at 60 degrees to give a maximum of three times secondary delta voltage. This theoretical value of three times voltage is not actually reached due to losses in the circuit and the impedance to the point of fault. Potential transformers of 200/100 ratio are used to compensate for this rise in voltage. Under normal conditions there is no voltage within the delta, so that this can be tested directly with a voltmeter in order to check connections. If there is zero voltage at the relay terminals, connections should be correct. Actual directional element tests can be made similar to those outlined in N.E.L.A. Relay Handbook. In this case it would be desirable to open one breaker on the loop and then work on the other to give proper directional indications. A 360 degree phase indicator will give results much easier to interpret than will the use of wattmeters or power-factor meters. Question 2 has been partly answered but it is suggested that circuit breaker 1 be opened and indications taken on breaker 2 with normal flow of power into the load. The directional contact will make in one position or the other, and the opposite contact from the one closed should be used for the trip circuit of circuit breaker 2. Circuit breaker 1 can then be closed and 2 opened to check further the connections. It might be well to emphasize that a short-circuit on a feeder may not cause balance current to flow in circuit breaker 1 and 2. Dependent of course upon the system connections it is quite possible that the current circuit in breaker 1 and 2 may not be equal. If such unbalance is of sufficient magnitude, this current may prove a factor which should be seriously considered. However, by proper selection of time settings and current settings proper operation should result. It will probably prove expedient to set the timing of circuit breakers 1 and 2 just a little bit higher than the usual low time setting that is used on balance protection. This will give the feeder circuit breaker a start on relays for circuit breakers 1 and 2, in case unbalance should exist. I. T. M.

2786—Calculation of Motor Efficiency at Reduced Speed—We have the performance of a 1000 hp., three-phase, 60 cycle, 2200 volt, 710 r.p.m. motor. The motor speed, efficiency, power-factor are plotted against horse-power. Then we have plotted the fan speed required to deliver certain volumes of air and plotted these speeds against the horse-power. What we want to determine is the efficiency of the slip ring motor when operating at the reduced speeds obtained by inserting resistance in the secondary. We have gone about this as follows, using the reduced efficiency formula from B. G. Lamme's article, The Polyphase Motor.

$$E_2 = E_1\left(\frac{100 - S_2}{100 - S_1}\right)$$

$$\text{for 1000 h.p., } E_2 = 94\left(\frac{100 - \frac{711}{720}}{100 - \frac{711}{720}}\right)$$

$$= 94 \text{ percent,}$$

$$\text{for 110 h.p. } E_2 = 67\left(\frac{100 - \frac{355}{720}}{100 - \frac{718}{720}}\right)$$

$$= 33.2 \text{ percent.}$$

In like manner we found $E_2$ for other loads. Then the true watts input

$$\text{for 1000 h.p., } = \frac{1000 \times 746}{94} = 794\,800$$

$$\text{for 110 h.p., } = \frac{110 \times 746}{33.2} = 247\,000$$

The watts for intermediate loads were similarly determined.

I would greatly appreciate it if you would tell me if these reduced efficiency and watts imput curves are correct. We are assuming that the power-factor will remain the same or even get a little better at constant or reduced speeds.

J. H. M. (COLO.)

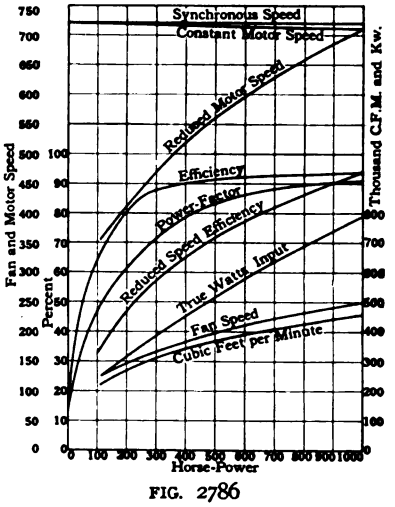



FIG. 2786

When the speed of a wound-rotor induction motor is reduced by external secondary resistance, the losses in the motor and the primary power-factor are determined by the torque. The additional losses due to the increased slip are dissipated in the resistance grids connected in the secondary circuit. The efficiency $E$, which you used was apparently determined from the motor curves as referred to the horse-power output of the motor, but should have been determined from the torque delivered by the motor. The factor used to get the actual efficiency of motor and control from $E_1$ is apparently copied incorrectly, since in every case it is greater than unity, yet the final result indicates that a factor less than unity was used. It would be best for you to replot the efficiency, power-factor, speed and horse-power curves with torque as the abscissa and then proceed as follows, checking 400 hp., 520 r.p.m. point.

$$\frac{\text{Hp.} \times 5250}{\text{R. p. m.}} = \text{Torque}$$

$$\frac{400 \times 5250}{520} = \text{Torque equivalent to}$$

560 h.p. in Fig. (a)

From this torque the following values are taken from curve:—

$E$ = 92.5 percent approximately

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85 percent power-factor and 715 r. p. m. approximately.

$E_2 = E_1 \frac{(1-S_2)}{(1-S_1)}$ $S_1$ and $S_2$ indicate slips at normal and reduced speeds.

$\frac{(1-S_2)}{(1-S_1)} = \frac{\text{R.p.m.}_2 \text{ (speed at reduced point)}}{\text{R.p.m.}_1 \text{ (speed at normal point)}}$

$E_2 = E_1 \frac{(\text{R.p.m.}_2)}{(\text{R.p.m.}_1)} = 92.5 \times \frac{(520)}{(715)} =$ 67.3 percent.

Watts input $= \frac{400 \times 746}{0.673} = 443\,000$

R. R. S.

2787—Unbalanced Voltage and Current in Waterwheel Generators—We have four similar waterwheel generators tied to an open delta bank of a step-up transformers (2300 to 11 700 volts). Is this arrangement the cause of any voltage or current unbalance at the generators? The load is supposedly balanced. Actual test data are shown in Fig. (a). If possible would like to get a procedure for calculating these.

H. F. W. (WISC.)

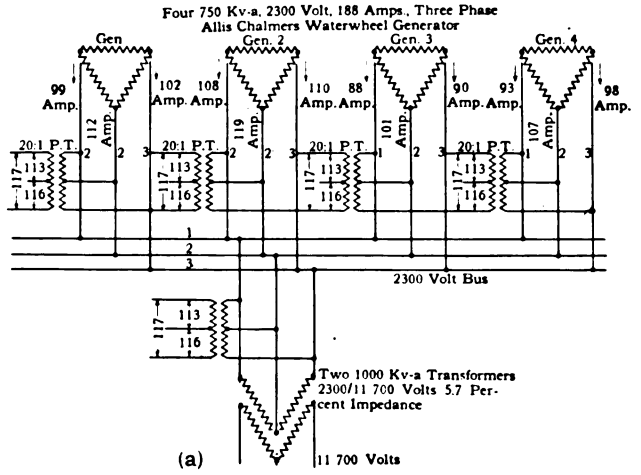


FIG. 2787 (a)

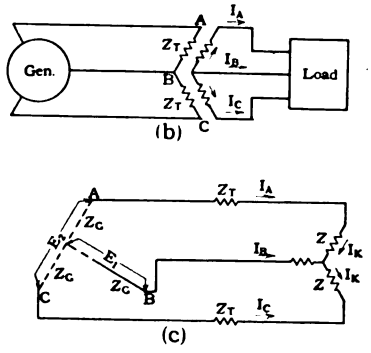


FIG. 2787 (b and c)

a—The arrangement of transformers shown in Fig. (a) is the cause of voltage and current unbalance at the terminals of the generators even with balanced load conditions since a transformer bank so connected introduces unequal impedances in different phases. b—The unbalanced currents in this case may be calculated by the following procedure. The transformer bank can be replaced by simple series impedances which will produce the same voltage and current conditions as the transformer bank. In Fig. (b) it is seen that the currents $I_A$ and $I_C$ flow through and thus experience the impedance which the transformers $AB$ and $BC$ respectively offer. $I_B$ is simply the resultant of $I_A$ and $I_C$. The bank may then be represented by a series impedance, $Z_T$, in branches $a$ and $c$ equal to the impedance of one transformer, Fig. (c). The load is replaced by an impedance, $Z$, which gives the same value of power and reactive volt-amperes as the actual load. The calculations will be simplified if we consider the quadrature internal voltages of the generator, $E_1$ and $E_2$. ($E_1 = -j\,0.866\,E_2$). Then,—

$$I_B = \frac{E_1}{Z + \frac{1}{2}(Z + Z_T)} \quad \ldots\ldots\ldots (1)$$

Since branches $a$ and $c$ are symmetrical about line $B$,—

$$I_K = \frac{E_2}{2\,(Z + Z_T)}$$

and since $I_A$ and $I_C$ result from both the voltages $E_1$ and $E_2$. We may superimpose the solutions:—

$$I_A = I_K - 0.5\,I_B \quad \ldots\ldots\ldots (2)$$

and

$$I_C = -I_K - 0.5\,I_B \quad \ldots\ldots\ldots (3)$$

From equations (1), (2) and (3) the values of line current may be calculated. If the synchronous impedance of the generator corresponding to the power-factor under which it is operating is known, then the terminal voltage may be found by subtracting from the internal voltage the impedance drop due to the line current. Before your test values can be checked, it is necessary to know the complete characteristics of the load and the generator. For a more extended treatment of the method of calculating the performance of the open-delta connection of the transformers see "Method of Symmetri-Co-Ordinates Applied to the Solution of Polyphase Networks," by C. L. Fortescue Trans. A.I.E.E. 1918, p. 1058.

D. C. H.

2788—Electrolytic Condenser for B-Eliminator Filter Circuit—I wish to build an electrolytic condenser to be used in the filter circuit of a B-elminator as illustrated in Fig (a). Will aluminum 99.2 percent pure be satisfactory for this type of condenser? What will be the capacity per square inch at 200 volts direct current? Are the connections with reference to plus and minus correct or should they be reversed?

L. B. S. (PA.)

In the diagram shown, an electrolytic condenser should be quite satisfactory as a $B$ eliminator filter and the grade of aluminum you mention will be satisfactory. Capacitance per square inch of anode surface at 200 volts direct current depends upon the voltage of forming the film by sparking at 400 volts or over, the film forms quite slowly with very heavy current at first. Such a film will have in the neighborhood of 6 mfds per square inch. The condenser made with borax solution

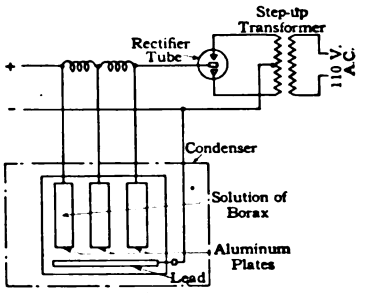


FIG. 2788 (a)

has a tendency to lose its film if it stands for two or three weeks without voltage applied. This results in a great rush of current and overloading of the rectifier tube when starting up. The polarity of markings and connections shown in Fig. (a) are correct.

L. W. C.

2789—Transformer Temperature Rise—1—What is the maximum allowable temperature for the oil in an O.I.W.C. transformer? (b) Of an O.I.S.C. transformer? 2—A 7000 kv-a O.I.W.C. shell type 11/89 kv transformer operates with an oil temperature 43 degrees C. What would the hot spot temperature of such a transformer be likely to be? 3—What is the allowable hot spot temperature for O.I.W.C. transformer provided with indicators of the current transformer-heating coil type?

R. B. G. (CALIF.)

1—The A. I. E. E. standardization rules fix the maximum allowable temperature of transformer oil at 90 degrees C. This would apply to either O.I.W.C. or O.I.S.C. transformers. 2—At full load the hot-spot temperature would very likely be from 15 degrees to 20 degrees higher than the oil temperature. A more definite statement is difficult to make without more knowledge of the type of construction and the basis of the rating. 3—The A. I. E. E. rules fix the maximum hot spot temperature of a transformer having the usual class of insulation at 105 degrees C. This would be the maximum limit for the indication of a temperature device which reads hot spot temperatures. In considering the maximum limits of temperature which are set by the A. I. E. E. rules, it would be well to recognize that these limits were adopted for the purpose of standardization only, and it would be conservative not to operate at the extreme limit of temperature either for oil or for hot spots. In this connection see A. I. E. E. Standards Bulletin No. 1, "General Principles Upon Which Temperature Limits are Based in the Rating of Electrical Machinery and Apparatus."

W. M. D.

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2790—TESTING A REPAIRED TRANSMISSION LINE FAULT—Our generating station has a layout in connection with transmission lines as shown in Fig. a. There are parallel lines feeding a main substation and that these lines are tapped at intermediate points. It is assumed that a fault has developed on the section marked *B*. Switches 1 and 2 have operated and cut out the faulty section. Repair work has been made and the apparent fault removed but it is not desirable to risk putting the section back into service without testing it to full pressure. Important substations are fed from sections *A* and *C*. So they should not have their supply interrupted or have their pressure subjected to heavy fluctuations, due either to shutting off their supply while section *B* is tested, or which might result from closing switch 1 or 2 if the fault still remained on section *B*. Is there any method of carrying out these tests, and what is the usual practice in cases similar to that indicated? A single ring main

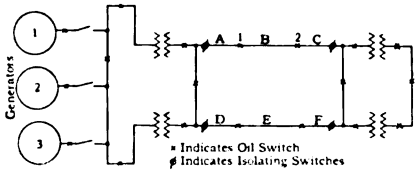


FIG. 2790 (a)

supplying a number of substations, with a fault between two substations would have somewhat similar conditions. H. J. H. (NEW ZEALAND)

The section of line *B* may be tested by "meggering" the line after all transformers have been disconnected from that particular section. It also may be tested by the use of a bank of transformers located at station 1 or 2. The capacity being 10 or 15 percent greater than that required to charge the section of line in question. In actual practice it has been found, by the use of the alternating-current automatic reclosing oil circuit breaker, that a large percent of line faults are cleared on the first closing after a circuit breaker has tripped out automatically. This would indicate that an elaborate means of testing is not necessary. If the relay system is correct and the circuit breakers have a trip free mechanism there ought not to be any objection to testing a line by closing either No. 1 or No. 2 circuit breaker. It might be added that in actual practice on 220 kv lines, tests are made in this manner. F. W. M.

2791—PHASE RELATIONSHIPS IN REVERSE POWER RELAY—Fig. (a) shows the proposed connections for operating a reverse power relay. Is the current in primary line 1 in phase with the secondary voltage *ab* and subsecondary voltage *xy*? By connecting the autotransformers as shown, will the current in the upper element of the relay lead the impressed voltage by 30 degrees? Please show by vectors the relation of the secondary voltage to the line currents. C. C. C. (ARIZONA)

Fig. (b) (c) and (d) gives a complete vector diagram for the circuit as shown in Fig. (a). The load drawn from the secondary side is assumed to be balanced and non-inductive as shown in Fig. (c), where $I_a$, $I_b$ and $I_c$ represent the line currents. These line currents resolve into the delta components $I_{ba}$, $I_{cb}$, and $I_{ac}$ flowing in the delta windings and which are balanced by the currents $I_1$, $I_2$ and $I_3$ flowing in the primary windings and corresponding lines. By a study of Fig. (b), (c) and (d), it may be seen that primary line current $I_1$, considered flowing into the primary winding, is in phase with secondary voltage $E_{ba}$ and sub-secondary voltage $E_{yx}$, but is 180 degrees out of phase with secondary voltage $E_{ab}$ and sub-secondary voltage $E_{xy}$. The con-

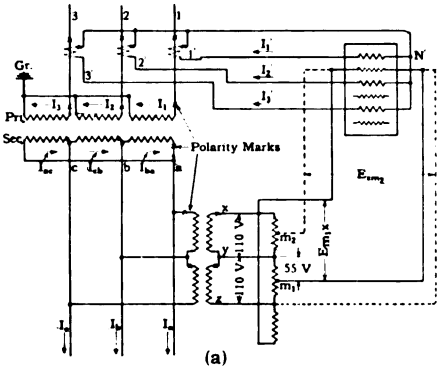


FIG. 2791 (a)

nections as shown in Fig. (a) will give a current in the upper element of the relay leading the impressed voltage on the potential coil by 30 degrees at unity power-factor. Since we are not familiar with all the features of this application, we are not prepared to say

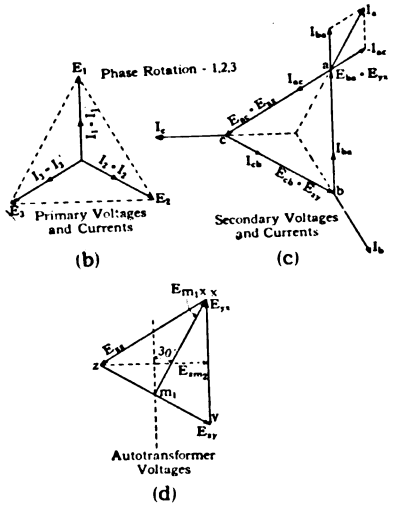


FIG. 2791 (b), (c) and (d)

whether this scheme of connection will give satisfactory operation in all cases if the relay is of the type where maximum torque is produced when the current lags the impressed voltage by approximately 45 degrees. With such a relay the scheme of connections usually considered standard are as shown in Fig. (a) with the potential coil connections modified as shown with dotted lines, wherein the current leads the impressed voltage by 90 degrees. The vectors illustrating the voltages used for 30 degrees and 90 degrees connections are shown in Fig. (d), where $E_{m1x}$ is used for the 30 degrees connection and $E_{m2}$ is used for a 90 degree connection. W. K. S.

2792—NATIONAL CODE RULES—I have a job coming up in the near future; a three-phase 220 volt installation for power and where it is desired to install also a transformer system to give 110/220 volts, single-phase for lighting. The diagram Fig. (a) shows the common system of using one phase of this system for the purpose. *1*—Is Fig. (a) permitted by the National Code? *2*—Is there any limit to the output of the transformer that is permitted by the National Code to be connected to one phase in this manner? *3*—Does this sort of a connection have any bad effects on the three-phase system, that is, anything that could be objected to by either the Underwriters or the Service Company? *4*—If two or three transformers were grouped to distribute the lighting as Fig. (b) the total load being 12 kilowatts each transformer taking care of 4 kilowatts. Would this be the proper way to connect them? *5*—Would it be proper to ground these transformers at the neutral point A? *6*—In Fig. (b) it will be noticed that the total load is 12 kilowatts and each transformer is taking care of 4 kilowatts each, but the transformers are 2 kv-a capacity output. Is this the proper size or where the load on the three-wire circuit is reasonably balanced what is the proper ratio of transformer output to connected load where autotransformers are used in this manner? *7*—The diagram (c) shows two transformers connected to

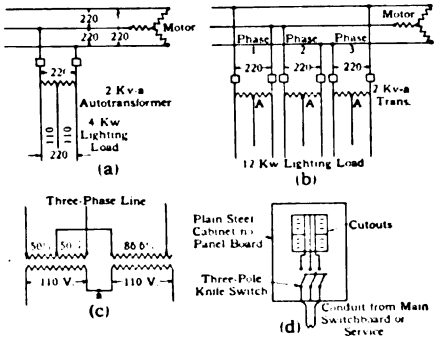


FIG. 2792

three-phase power lines and transforming the current to single phase. This diagram I saw in Hawkin's Electrical Encyclopedia. Can a neutral be run out from point *A* and get 110-220 volts for three-wire single-phase lighting? Is it approved by the Underwriters? Is there any special transformer of this kind on the market? *8*—In section 1202 (a) National Code Installation of Switches, will the common knife switch placed in a steel distribution cabinet controlling the feeder or subfeeder for same, be approved providing it is not located in wet places or places that are dusty or contain inflammable gases, etc., or is it required that all common knife switches be mounted on switchboards or panel boards? *9*—What is meant by back wiring spaces as mentioned in Section 702 (b)? J. H. D. (MO.)

So far as we are aware the questions brought up under headings, *1*, *2* and *3*, are not touched on by the National Code. We see no reason why any fire underwriter should object to this installation, as there is nothing in the connection itself which would involve a fire hazard provided the wiring is properly installed. If the arrangement shown in Fig. (a) is adopted, we would recommend that the neutral of the autotransformer be grounded, taking care that there are no other grounds

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on the secondary system. Before installing a system of this type you can consult with the local representatives of the underwriter's. The arrangement shown in Fig. (a) might possibly be objected to by the service company it the lighting load is a large part of the total load. In such a case the use of three transformers to distribute the lighting load on the three phases as shown in Fig. (b) would be much better. In this case it would be impossible to ground all of the autotransformers at the neutral point marked *A* as this would amount to a short-circuit. This difficulty could be overcome by installing a one to one ratio two winding transformer. *6*—The ratio of the capacity of the autotransformers to the total load depends upon the amount of total unbalance. The autotransformer should have a rating equal to the maximum unbalance. *7*—The diagram in Fig. (c) shows the Scott connection for transforming from three phase to two phase. A neutral run-out from point (a) will give you two-phase three-wire secondary. This is a relatively common connection but we believe transformers for this purpose have to be ordered with special taps brought out during the process of manufacture, which means that a special transformer must be ordered. There is no particular reason why the underwriter's should object to this connection, but it is by no means as effective as a three-wire single-phase lighting system. The connection, Fig. (c), gives 155 volts between the two outside lines on the secondary and 110 between each outside line and the neutral, with a greater voltage drop than the ordinary single-phase three-wire circuit which has 220 volts between outside lines. There is no way of transforming from three phase to single phase. *8*—The present tendency is to interpret section 1202a as meaning that practically all knife switches should be of the totally enclosed so called safety type unless mounted on a standard switchboard or panel board. This however is up to the local inspector and you should consult him about such an installation. *9*—Rule 702b means that there must be space between the back of the cabinet and the device mounted therein for running wires to the devices, where there are more than four circuits, unless the wires leave the cabinet directly opposite their terminal connections. This latter requirement is usually met so that the back wiring spaces are usually not required in ordinary cutout boxes. C. R. R.

2793—Brush Sparking—What causes a brush to have a glassy contact surface? Does it indicate good operation? I have a machine on which the positive brushes show most of this kind of surface but the contact in the center has a sooty appearance. All brushes spark but negatives spark least. All similar brush spacings are accurate to 1/64 inch. Shunt poles have equal turns and equal drop and equal gaps. Armature is well centered and has equalizer connections. Commutator is true. R.p.m. 600, 250 volts, 2000 amperes, 160 bars, 160 slots, 1 bar per turn, 2 conductors per slot, brush covers 2 1/3 bars. No. workmanship defects, grounds or shorts. M. E. J. (MICH.)

A glassy surface at a brush contact may or may not indicate successful operation of the brush and good commutation. If the load on a machine is light, the commutation may be good and the brush have a glassy surface at the contact, while the same machine may have very bad commutation and a burned brush surface at the contact with higher loads. Sometimes, even with bad commutation, a brush has a smooth and glassy surface at contact, but shows a burnt appearance in the leaving edge of the brush on the surface radial to the commutator. This burning generally extends on the brush surface 1/8 in. or less away from the commutator. The nature of the sparking accompanying this type of brush burning is generally bluish snappy sparking in the trailing edge of the brush. Sometimes this burning occurs under one polarity brush as compared to that under the other polarity. This is generally due to a wrong grade of brushes for the particular application, or to an inherent defect in design of machine, or a wrong compensation of the commutating pole, or a combination of any of these three factors. A change of grade of brushes may eliminate or minimize this particular trouble, or a change in the air-gap of the commutating poles may help. C. L.

2794—Meter Constants—What constant will be used under the following conditions, Fig. (a)—Power transformers connected star-delta, 32 482 to 240 volts; series transformers, ratio 20 to 5; potential transformers second reduction, ratio 200 to 100 volts; for an integrating wattmeter, 5 amperes, 100 volts; and a graphic recording wattmeter 5 amperes, 100 volts? L. C. H. (N.Y.)

If you are using only two 20-5 current transformers on the high tension side of your power transformers the meter will measure only ⅔ of the power when the load is balanced. It will not measure unbalanced loads correctly. The primary voltage of the power transformers is the line to neutral voltage and is 57.7 percent of 32 482 = 18 754 volts. This is reduced to 120 volts which makes an overall potential transformers ratio of 156.28 to 1. The current transformers have a ratio of 20-5 or 4-1. The total transformer multiplier will then be 156.28 times 4 or 625. This would be the multiplying constant to use provided the

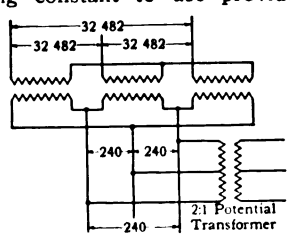


FIG. 2794 (a)

meter was reading correctly but as it measured only ⅔ of the power of this value will need to be multiplied by 1.5 making the multiplying constant equal to 937.5. This constant applies only when the load is balanced. If you are using three 20-5 current transformers in the high tension side with secondaries delta connected and also correctly connected to the meter, the meter will measure correctly the total power regardless of unbalance and the multiplying constant will be the product of the potential and current transformer ratios or 625. In any star-delta transformer bank there is a 30 degree displacement between the primary and secondary voltages. If the potentials for the meter are taken from the low side and the current transformers are in the high side the usual polyphase meter connections are no longer correct because of the 30 degree displacement but this difficulty can be overcome by using three current transformers with the secondaries connected in delta. C. O.

2795—Paralleling Frequency Changers—What is the proper method of testing before paralleling frequency changers and also the correct method to adjust sets for parallel operation, should the shifting of motor stators have a tendency to make it difficult? We have one motor, rated at 290 hp, three phase, 25 cycles, 6600 volt, 750 r.p.m., with adjustable stator frame connected to 200 kw generator, three-phase, 62.5 cycles, 110 volts, 750 r.p.m. which will be used for a single-phase load. The generator frame cannot be shifted. The above set is to be paralleled with a generator, rated at 100 kw, three-phase, 62.5 cycles, 110 volts, 750 r.p.m., has a non-adjustable frame and carrying a single-phase load. The motor of this set is 150 hp, three-phase, 25 cycles, 6600 volts, 750 r.p.m. The motors of these sets will receive their current from the power company as individual units, but the generators will be paralleled. The exciters are direct connected to each set, each exciter is to be regulated with a separate Tirrill regulator. As the frames of the motors are adjustable and the generator frames are stationary, if the frames of the motors are set differently, will it affect the relative position between rotor and stator and what abnormal condition, if any, can I expect when paralleling generators? We have one set now running and there seems to be a striking sound (not mechanical) in the motor which made me wonder if the position of motor frame were the cause. One of the engineers explained it as a cycle harmonic. This set, however, is carrying full load continuously without signs of undue heating anywhere. If the setting of frames must be in a certain position what is the proper procedure? Also, when paralleling generators can I expect difficulty getting sets together if motor frames are not set the same? Will generators divide load properly? W. J. S. (NEW JERSEY)

The successful operation of one or more synchronous frequency changer sets depends upon several factors. First it is necessary that the frequency of the two systems remain constant. Also, the ratio of frequencies of the two systems be exactly the same as the ratio of the number of poles of the motor and generator of the set. In this particular case if the power supply for the motor is 25 cycles, the system to which the generator is connected must be exactly 62½ cycles and not 60 or 65. The one exception to this is the case where the frequency changer set is of sufficient capacity to change the frequency of the system to which it is connected. The steps necessary to put one frequency changer set on the line and parallel another with it depend upon the mechanical construction of the sets and the available instruments for paralleling. If the two sets are not duplicates, it is probable that the

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two generators' fields do not occupy the same physical position on the shafts with reference to the two motor's fields. We will assume that they do not occupy the same respective position. This then makes it necessary to have frame shift provision on either the motor or generator of each set. We will further assume that the shifting device is manually operated and not motor operated. Also, that a synchroscope is not avilable. First, start and synchronize the 25 cycle motor of set number one. The alternating-current generator is unexcited and disconnected from the 62½ cycle system. Second, adjust the excitation of the generator of set number one to give a no-load voltage equal to that of the system to which the generator will furnish power. For determining the synchronizing position either lamps or voltmeters may be used. In the case of a two or three-phase load two lights will be required for the generator. For a single-phase load one light will be sufficient. The lamps should have a voltage rating of twice the normal voltage of the generator. In case this is excessive, step-down transformers should be used with the lamps. An alternating-current voltmeter may be used in place of a lamp, either with or without a potential transformer depending on the voltage of the generator. A volt-meter will probably be found more satisfactory as it will give a quantitative reading for the difference in potential due to phase displacement between the generator voltage and load voltage. This difference in potential may be so small as not to light the lamps. For these particular sets with single-phase generators only one alternating-current voltmeter is required with a voltage range not less than 250 volts. Third, connect one generator lead to the line and the other through the voltmeter to the other side of the line. If the voltmeter reads zero, the generator voltage is in phase with its system voltage. Remove the voltmeter and connect the other lead directly to the line. The set will then take its load. However, if the voltmeter swings from zero to twice the generator voltage, this means the generator is not running at the same frequency as that of the load. It cannot be paralled with the load unless the frequency of one system is changed. If the voltmeter reads a steady value, the generator and load have the same frequency but their voltages are not in phase. There are four possible chances to get them in phase. The motor and generator field may be reversed. Suppose the voltmeter reads a steady value. Note down this value. Fourth, disconnect the generator leads. Reduce the excitation on the 25 cycles motor to the lowest value at which it will stay in step. Reverse the motor field. Connect the generator leads back as before and note the voltmeter reading. If it reads zero, the generator may be connected to its load. If it does not read zero, note down this value. Fifth, disconnect the generator leads as before. Reduce the generator field excitation to as low a value as possible and then reverse it. Increase the excitation of the generator back to that value for normal voltage. Connect the generator leads as before and note the voltmeter reading. Sixth, again record the voltmeter reading, if it is not zero. Reverse the motor field again as previously described and note the voltmeter reading. Providing it is not zero compare the value of the four readings taken. If necessary change both the motor and generator fields to correspond to the polarity, which gave the lowest voltmeter reading. This then is the position nearest to synchronism for the set without shifting the frame of the motor. Seventh, disconnect from the line both motor and generator. After the set has come to rest unloosen the bolts holding the cradle frame and shift it slightly. Tighten the bolts and start up the set again. Note the voltmeter reading. It will indicate if the frame has been shifted in the proper direction and approximately how much more if at all, it must be shifted. Continue to adjust the frame shift until the voltmeter reading is zero. The first set is now ready to connect the generator to the line and will take its load when connected. The problem of paralleling a second set with the first set is very similar to the one just described. As before, assume that a synchroscope is not available. A direct-current ammeter for the field of each generator and an alternating-current ammeter with a scale greater than full load current of the largest set will be necessary. Eighth, start up and synchronize the 25-cycle motors of both sets without excitation on either generator. Find the field current to produce approximately 40 tc 50 percent normal voltage for each generator. Check carefully to see that this voltage is the same on both generators. Ninth, with the generator unexcited short-circuit the armature through an ammeter. Increase the excitation slowly on both generators to the value just determined. Note the ammeter reading. If there is no deflection, the generators are in synchronism and will take their respective loads according to the regulation of the two sets. Tenth, reduce the excitation on each generator. Disconnect their armature leads. Excite each generator to its normal voltage value and switch it on the line. Eleventh, if the alternating-current ammeter reading is not zero, note down its reading. Decrease the excitation of both generators. Open the short-circuit of their armatures. Reverse the excitation of the generator on set number two. Reconnect the armature through the ammeter and bring the excitation of both generators up to the previous value. Note the ammeter reading. If none, the two sets can be put on the line as described in ten. Twelfth, if there is an alternating-current ammeter reading, again note this down. Disconnect the armature of the generators and shut down set number two as previously described. Reverse the field of the 25-cycle motor on set number two. Start up the set again and proceed as before to find the alternating-current ammeter deflection. Thirteenth, if there is still a current circulating between the machines, there is one more possibility. Reverse the field of the generator on set number two and note the alternating-current ammeter reading. Compare the four readings of the alternating-current ammeter. That combination of excitation of both machines on the second set which gives the minimum circulating current between the two generators is the nearest the two sets can be paralleled without frame shift. Fourteenth, carefully shift the frame of the motor on set number two until the alternating-current ammeter reading is zero. The generators are now in synchronism. The accuracy of paralleling the two sets in the above steps depends entirely on how accurately the field currents of the two generators are adjusted each time to give the same voltage on both generators. The cradle frame of the second set is now bolted solidly in place. The two sets will now operate satisfactorily in parallel and divide their load according to their rating and regulation. Fifteenth, reduce the excitation on both generators to zero. Open up the armature short-circuit. Excite the generator on set number one to give normal voltage. Close the switches connecting the generator to its load. Then excite the field of the generator on set number two for normal voltage and connect directly on the line. There will probably be some oscillation when the sets take their load in this manner. This can only be elminated by a motor operated frame shifting device. Lastly, adjust the field current on both generators for the desired power-factor. R. L. F.

2796—RATE OF WATER FLOW IN TUNNELS—The data given us on the tunnel to our hydro station is that we may increase the flow from zero to 3000 c.f.s. in not less than three minutes. Would the rate be the same if 1000 c.f.s. were already flowing to 3000 c.f.s. in two minutes? It looks to me like a bigger change from nothing to something than from something to some more and I should think it would be harder on the tunnel. J. J. H. (CALIF.)

The data on the tunnel problem is rather incomplete, so that about the best we can do is generalize as follows:—If the head is low, the time of acceleration from 1000 to 3000 c.f.s. would probably be proportionately longer than from zero to 3000 c.f.s., since the friction head drop at the higher velocities retards, to a certain extent, the rate of velocity increase. If the head is high, the difference in rate will be very little, because in this case the friction head forms a smaller part of the total head in accordance with usual practice in design. If the effect of friction is disregarded there would theoretically be no difference in the rate of increase in velocity. H. E. P.

2797—SECONDARY LEADS OF CURRENT TRANSFORMERS—What is the limiting factor of the length of the secondary leads of a current transformer. It is proposed to install watthour meters about 100 ft. from the transformers. What rule is used to determine the cross-section of secondary leads. H. C. O. (NEW ZEALAND)

The limiting factors in determining the size of secondary current transformer leads are the type of transformer used and the nature of the secondary burden or load. In the case of the watthour meter, the secondary load is very low, probably it would not exceed 1½ to 2 volt-amperes. If the current transformer used is rated at, say, 10 volt-amperes compensation, then the secondary loading represented by the leads should not exceed the difference between the transformer rating and the meter loading. For example, assuming two volt-amperes for the meter with a 10 volt-ampere transformer, the impedance of the secondary leads should be limited to eight volt-amperes. This impedance can usually be considered

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as resistance since the wires are almost invariably twisted or placed close together with a result that there is little or no reactance. The resistance is therefore equal to eight volt-amperes divided by normal full-load current of five amperes squared, or 0.32 ohms. This would work out that a very small wire could be used. Of course, in actual practice it is not advisable to use anything less than No. 10 B & S gage wire for secondary runs and since No. 10 wire has about 1 ohm to a 1000 feet, and there will be approximately 200 ft. of wire, the resistance of this secondary wiring would be in the neighborhood of 0.2 ohm. H. A. T.

2798—Operating 25 Cycle Motor at 3000 R.P.M.—It has been suggested that a standard, wound-rotor 25 cycle induction motor with a three-phase rotor and a three-phase stator, could be operated at 3000 r.p.m. for direct connection to pumps by connecting both primary and secondary to the supply circuit, the proper phase reduction being used. Would you kindly advise if this is a practical method of securing a 3000 r.p.m. motor?

C. H. C. (PENNA.)

A wound-rotor induction motor can be so operated but with the difficulty that it will not come up to speed. It is necessary to bring the rotor up to a speed of 3000 r.p.m. by some external means before applying voltage to the rotor; and also to apply exactly the proper voltage to the rotor to correspond to that produced in the rotor winding by the primary voltage. Under these conditions the motor will operate at synchronous speed. The mechanical construction of the rotor must be such as to withstand the speed of 3000 r.p.m. Most commercial two pole, 25 cycle, wound rotors are not built to withstand such a speed. O. C. S.

2799—Rating of Three-Phase Two-Phase Transformers—On our system are two interchangeable transformers each rated 25 kv-a, 4000-230 volts, 60 cycles, 55 deg. C. These transformers were purchased for delivering continuous rated output when Scott connected to a 4000 volt three-phase supply and delivering 230 or 460 volts two phase. What will be the percent increase over the name-plate rating of each of these transformers if operated as straight single-phase units, that is, from 4000 volts single phase to 230 or 460 volts single phase? Please explain in detail.

R. D. E. (TEXAS)

This problem is readily solved by means of the equations in an article by E. G. Reed in the JOURNAL for March, 1919, p. 96, or in "Essentials of Transformer Practice", by E. G. Reed, pp. 288-290. A study of these equations shows that, with identical transformers, the ratio of the kv-a rating to the kv-a transformed on the three-phase side equals 2.31 divided by 2.0 = 1.155; whereas on the two-phase side the kv-a rating is the same as the kv-a transformed. This means that when transformers which are rated for a Scott connection are operated as straight single-phase units, the theoretical rating of the three-phase winding could be increased by 15.5 percent, but the theoretical rating of the low-tension side could not be increased at all. However, at normal rated load, when operated as straight single-phase units, the copper loss on the high-tension side of the above transformers would be less than normal and hence the total transformer temperature rise would be less than normal. With such small differences in rating, the low tension winding could readily carry some (say 7.5 percent) more current than normal, for the reason that the decreased high-tension losses would just about make up for the increase in low-tension losses. In other words when operated on straight single-phase, these transformers could be rated 7.5 percent higher than when operated with the Scott connection. Specifically, transformers which are rated at 25 kv-a when Scott connected, would be rated at 26.88 kv-a when operated on straight single-phase. C. R. R.

2800—Cooling Coils and Water for O.I.W.C. Transformer—1—If an oil-insulated, water-cooled transformer will carry rated load at its guaranteed temperature rise, how much load will it carry if the amount of cooling water passing through the transformers cooling coils is doubled? 2—In the design of cooling coils for large ttransformers, approximately what inlet pressure is usually selected? 3—What, if any, relation exists between the hot spot and average temperatures of large O.I.W.C. transformers?

R. B. G. (CALIF.)

(1) The normal rate of cooling water for an O.I.W.C. transformer is usually of such value as to give approximately 10 degrees C. rise between inlet and outlet temperature. In other words, 25 degrees C. cooling water temperature at the inlet would have an outlet temperature of 35 degrees C., or an average of 30 degrees C. By doubling the water rate, the temperature rise of the water will be reduced to one-half the original value, and with an inlet temperature of 25 degrees C. the outlet will be 30 degrees C., the average, 27½ degrees C. The effect of reducing the average temperature of the inlet and outlet water 2½ degrees will be about the same as lowering the inlet or ambient temperature the same amount and keeping the water-rate the same. In general, a lowering of the ambient of 2½ degrees will permit approximately three percent greater load to be carried with the same ultimate temperature. This statement is based on conditions found in the average water-cooled transformer. (2) An arrangement of cooling coils is usually selected so that the water pressure required at the transformer does not exceed 25 lbs. per sq. in. (3) The difference between hot-spot temperature and average winding temperature (as measured by resistance) can be measured only by laboratory methods. The conventional allowance for this difference is 10 degrees C. This figure has been adopted by the A. I. E. E., as a standard (Section 1, rule 7, A. I. E. E. Standards).

H. L. C.

2801—Frequency-Changer Exciter Voltage—Will you please explain the reason for the following mishap. We have a 360 kw, 480 volt, 60 cycle generator, direct connected to a 525 hp, 25 cycle, 4000 volt synchronous motor in service as a frequency-changer set. The excitation current for both motor and generator is supplied from a 125 volt, 13 kw exciter, also direct connected. Twice during the past year the direct-current voltmeter on the exciter panel has been destroyed. This instrument is connected to the line side of the generator field switch and protected by five ampere cartridge fuses. On both occasions these fuses have been blown completely out of the clips of the fuse block and the automatic oil circuit breakers on both the 480 volt and the 4000 volt panels have opened. After the first shut down the fuses were replaced and a new voltmeter connected in place of the burned out instrument. The machine was again started and appeared to be operating normally for several months when the same accident happened again. An investigation, after the second occurrence, disclosed an open contact in the field rheostat of the synchronous motor. Since this was repaired the machine is apparently again running normally. In checking our voltage on the motor panel we find a fluctuation from 3800 to 4100. The load on the generator is approximately 250 kw. What causes the heavy current to our exciter and how can we protect our instruments?

W. E. S. (CANADA)

The trouble described as occurring can undoubtedly all be traced to the open contact in the field rheostat. What probably happened was that a momentary opening of the faulty contact in the motor field rheostat occurred, resulting in the collapse of the motor field. As is well known, the armature current of a synchronous motor depends upon the load and also the excitation. The armature current for a fixed load is given by the vector expression $I_a = (V - E_a)/Z_s$ where $V$ is the terminal voltage of the motor; $Z_s$ the synchronous reactance; and $E_a$ the generated voltage due to the field excitation. Due to the loss of the voltage $E_a$, the armature current rose to an abnormal value in an extremely short period of time, thus inducing a high voltage in the field winding. This voltage arced across the open contact. The current incident to the induced voltage burned out the voltmeter. The large armature current caused the motor circuit breaker to open. With the tripping of the motor circuit breaker, a reversal of power would occur at the generator causing the generator to run as a motor. If reverse-power relays were used the generator circuit breaker would open. The collapse of the motor field would induce a relatively high voltage in the field winding but it is improbable that this in itself would cause the damage. The voltage fluctuation between 3800 and 4100 volts will not have any appreciable effect. If the field rheostat is not open there is no danger of the voltmeter being injured so no special precautions should be necessary other than keeping the rheostat in repair. P. H. R.

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# THE ELECTRIC JOURNAL

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## Alternating-Current Networks*

The increasing use of alternating-current networks in congested districts is striking. Five years ago there was only one small automatic network system, that of the United Electric Light and Power Co., in New York City. Today there are 22 cities operating or installing at least 50 of these networks, and there is a prospect that the number of cities will total 40 by the end of the year. They extend from Minneapolis and Seattle on the north to Buenos Aires on the south and from the Atlantic Coast to the Pacific. In all, there are more than 2500 transformer banks and protectors. In one city the plans called for networks totalling 600 000 kv-a within ten years. The performance of numerous systems shows that, when correctly installed and maintained, they afford a big improvement on previous methods of distribution in areas of congested load.

As with any new system, numerous problems arose which threatened to interfere somewhat with the success of the innovation, but each in turn is being cleared away satisfactorily. All this work on the part of the operating companies in the interest of improved service has involved a hugh effort and considerable expense. Accompanying these has been the heavy responsibility that attends not only any extensive changeover, but the making of that change in the most important load center of the system—the heart of the business district.

It was inevitable that the development of such extensive networks should involve the necessity for a certain amount of new equipment. First came the job of designing and constructing an automatic network protector on a large scale. To say that it was a new form of automatic switching equipment is only half the story. There were the extremely small space requirements, to permit passing through standard manhole openings; the task of operating and maintaining a "substation in a manhole"; and the introduction of several new functions for automatic equipment. All this development, of course, had to be done under pressure, due to the necessity of meeting definite construction schedules.

As system after system was started, new difficulties cropped up, due to the different conditions. It was necessary for the design engineers to live with these, and perfect the protectors step-by-step as experience was gained. Furthermore, every type had to be made applicable to any network system, as far as possible, in order to keep down the number of different types.

More recently there have been the new developments in network transformers to meet increasing ratings, in the face of difficult conditions of installation, cramped manholes and unusual temperature limitations. There have also been introduced the grounding and disconnecting switch on the high-voltage side, a compact internal tap changer, and shunt iron for increasing the impedance.

The protectors have sometimes been dubbed network switches or circuit breakers. If they were only what the name implies, then the temperature rise and ability to rupture heavy currents would be about the principal features. On the contrary, having determined on a 50 degree C. rise over an ambient of 40 degrees, and a rupture capacity of the order of twenty-five times the protector rating, the latest requirements call for a host of other features.

The master relays need to have almost human intelligence**. They must trip the protector on reverse power, to isolate a ground or phase-to-phase short-circuit on the feeder or in the transformer. They must even trip on the small reverse current due to the losses of the transformers when the feeder switch at the station is opened. But they must not trip on a secondary fault, even if it is attended by a reversal of current in one phase, as with some single-phase faults to neutral. They must close the protector automatically only when the resultant power flow of all phases will be from the transformer into the network. This includes closing on a dead network when the feeder is energized.

In their latest form, the relays also meet two former difficulties. If the load on one phase is too light to warrant closing, but is heavy enough on the other two phases to require closing, the relays cause the protector to close. And pumping can no longer occur when the feeders have three-phase regulators or two single-phase regulators in open delta without mechanical or electrical connection. Nor can it occur with high-voltage feeders should some protectors be a little slower than others in tripping when the station switch is opened.

Some of the other factors entering into the design are high torque in the relays, least number of contacts in the control circuit, a circuit breaker thoroughly reliable in tripping and closing, adjustments few in number and not too fine, back-up fuses that will blow when required, precautions against corrosion, perfect watertightness of the subway housing, foolproof and safety features, various aids in testing and maximum accessi-

*Based on a symposium on this subject, Pittsburgh Section A.I.E.E., Jan. 10, 1928.

**These relays and the latest type network protectors were described by Messrs. Grissinger and Parsons, in the JOURNAL for Dec. 1927.

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bility to minimize the work of maintenance and repairs. Simplicity and ruggedness, interchangeability of parts in the various sizes and types, and finally minimum noise, size, weight and installation cost, are also important considerations.

The equipment now available embodies all of these features as a result of several years of experience. Reports from the field show that even with the protectors of older designs, the alternating-current network is a big step ahead in distribution practice, and that the low-voltage network system is no longer an experiment, but a proven tool. Being man-made, it has its limitations. Let us recognize these and take proper precautions against them, such as by giving the equipment adequate maintenance. But it is time to realize what a fine tool it really is and to use it wherever feasible.

H. RICHTER

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**A Persistent Fallacy**

Time-worn is the notion that the introduction of new inventions causes general unemployment. This thought was nevertheless expressed recently in a trade journal, in an article referring to the Televox, described in our December issue. The writer concluded his discussion as follows:—

"Where day and night service is required each mechanical man will displace three workers, if eight-hour shifts are worked. So these automata, working 24 hours a day without wages, deaf to the strike call, will displace thousands of human workers who must eat and sleep and support families."

The fallacy in this thought is evident to one who looks further into the effect of a new invention than to just the immediate social adjustment that is necessary. Speaking materialistically it is evident that the goal of society is to obtain the maximum of comforts with the minimum of effort. It is likewise evident that any machine that will do the work of one or more human beings, and do it better, will help move society a step nearer this goal.

Society is never static; we are forever striving to satisfy our insatiable desire for possessions. Labor saving machinery decreases the cost of production. This increases the market for established goods and opens a market for new products. Thus, a new invention does not tend ultimately to throw men out of work, but rather to increase the total volume of products manufactured. Historically this tendency toward increasing the total number of products persists until the value of leisure time exceeds the value of products, when there is a reduction in the length of the working day. Since the beginning of the age of invention these forces have been at work, until now we have more of material wealth and work fewer hours a day than ever before. It is significant that the greatest average prosperity coincides with the maximum use of labor saving machinery.

Pernicious as the fallacy under discussion is, its error is less significant than its persistence, both present and past. The idea is not new. During the industrial revolution in England this notion excited frequent uprisings. At that time the introduction of the power loom caused general panic in the industrial classes. Again, in America, the introduction of the cotton gin was accompanied by wide and loud objection.

We must simply admit that this fallacy is historically a part of human thought, and will be a part of human thought until man has developed beyond his present intellectual viewpoint. It is an interesting example of the friction that is forever resisting progress.

ROGER L. KNIGHT

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**It's the Limit**

One of the interesting and valuable characteristics of a physical or mathematical analysis is that frequently more can be learned from a study of what is not, than from a study of what is. That is, carrying an analysis to its ultimate limits of zero or infinity or whatever they may be is frequently much more illuminating than an analysis which is confined to narrower limits.

Suppose, for example, it is desired to study the effect of a decrease in air-gap on the power-factor and other characteristics of an induction motor. The practical limit of the air-gap is purely mechanical and is concerned with such details as accuracy of machining and assembly, and subsequent wear of bearings. The limit is zero. With perfect machine work, with an unbending shaft, and bearings that would never show any signs of wear, an air-gap very closely approaching zero could be obtained. But the expense of attempting more accurate machining than the very close tolerances already customary would be great. And if it can be shown, as is actually the case, that reducing the air-gap to zero would improve the performance characteristics of the motor but slightly, why bother with any change along this line.

Again suppose it is desired to improve the efficiency of the same motor by reducing its losses. The limit is 100 percent efficiency. If the losses could be eliminated entirely, the motor would still be worth only a certain increase in price—equivalent to the capitalized value of the saving in power. This is true, of course, of any electrical apparatus. While this relation is well known, it is frequently overlooked and the importance of efficiency improperly evaluated. Many executives consider that a dollar of price difference today is worth more than several dollars of capitalized saving in the somewhat hazy future. On the other hand some engineers place too high a value on such capitalized savings.

Two examples of this method of analysis appear in this issue. The transient stability limit of a transmission system depends, for one thing, on the speed of response of the synchronous apparatus to the effect of quick-response excitation, when there is a disturbance on the system. The limit of the exciters, obviously, is instantaneous response—zero time. The small gain over

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the more possible conditions obtainable with such a response is analyzed in this issue by Mr. Robinson.

The characteristics of a long transmission line have much light thrown on them by a study, such as that in this issue by Mr. Boddie, of a line of infinite length. Of course, no such line is possible. Many of our commercial lines are, however, already getting so long that at 60 cycles some of the characteristics which are most strikingly illustrated in the case of an infinite line are of great practical importance. And at one thousand times this frequency, in other words at the frequencies commonly used for carrier-current telegraphy or signaling, existing lines are already longer than necessary to reproduce the characteristics of an infinite line. To one who is used to considering that the capacitance of a line is proportional to its length, it is startling to note that beyond certain limits an increase in length actually decreases the effective capacitance. It is only by carrying an analysis to apparently absurd limits that some of these interesting and frequently valuable characteristics can be determined.

CHAS. R. RIKER

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**Organization and Man Power**

An industrial organization consists primarily of a group of *men* organized to spend a certain amount of *money* by prescribed *methods* using proper *materials, buildings* and *equipment* so as to make things that can be sold at a *profit.* Of these various elements, men are the most important, as the biggest part of the problem of management is the proper co-ordination of men. The human element is more important than all of the machinery, buildings and other equipment. Management is now realizing the truth of this and is being more human than formerly. The men in charge are thinking more in terms of people, personality, individuals. They are considering their employe's likes, dislikes, feelings and emotions. They are giving more attention to the proper handling of men than to the handling of materials. If workers do not get pleasure out of their work, they do not get much pleasure out of life, because so much of their time is spent at work.

Management realizes its responsibility to make working conditions as satisfactory as possible—to make them such that men can take real pleasure in their work. Organization in industry is a team affair. Industrial success is measured largely by ability to co-operate and work together as effective individuals and as a group for mutual advantage. This requires loyalty to the organization—to the group—to the organization leaders.

Loyalty is a broad term; it signifies a great deal. It is very difficult to be completely loyal, though many probably think they are reasonably so. If a supervisor wants his men to be loyal to the whole enterprise, he must first have them be loyal to him—this he cannot do unless he has their respect. To build up a group of loyal, effective men is the biggest problem of supervision.

Training and developing men is a long time job. It calls for patience and vision, yet it is not always recognized that training and developing to the utmost capacity every workman and every foreman is of paramount importance.

In developing esprit de corps we must find a way to get men not only to think, but also to feel. How men feel is far more important than how they think. Their feelings govern their actions and measure their progress. A man may think right but, unless he feels right, he does not act as he should.

In any large organization it is necessary to have men of all kinds. The skilled artisan is a very important element. It takes a long time to develop the craftsman, the man who is an expert in a mechanical way. This is also a big problem of industry. There is a false notion in the minds of some parents as to manual work. Many of them want their children educated so they will not have to do physical work. It is hard to measure the value of a man who is skilled with his hands and is also educated to use his head. The value of the skilled artisan to industry is steadily growing. We must find a way to break down the prejudice against working with the hands. There are plenty of applicants for white collar jobs, but there are not so many who wish to become skilled tradesmen. It is not generally realized that it takes a high degree of mentality and intelligence to become an expert mechanic. Such a man is more valuable to industry than the other man with the same mental equipment, but lacking mechanical training. The educational problem thus becomes one of considerable magnitude.

It takes a good many types of men to make up a modern large industrial organization. Management's responsibility is to direct each group effectively, so as not to waste the money of the stockholders. This calls for team work, and team work calls for leadership. Each of the supervisors must be a leader of his group. Thus it is necessary to have a carefully planned organization. Right methods must be used, right men must be available, quality must be maintained and the product must be shipped at the required time at as low a cost as possible.

The major task of management is so to conduct itself as to get the co-operation and loyal support of the men in the organization. Manufacturing is a highly competitive business. Hence, it is highly important that the business sense be inculcated into every individual throughout the organization.

The leader in industry is quite like the leader of an orchestra. He chooses the piece to be played, selects the players, trains them and directs them to play in harmony so that the result is an effective production.

R. L. WILSON

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# Forced Air-Blast Equipment for Oil-Immersed Transformers

L. H. HILL
Transformer Engineer, Sharon Works,
Westinghouse Electric & Mfg. Co.

OCCASIONALLY it becomes desirable to provide oil-immersed, self-cooled transformers with means for blowing air on the cooling surfaces to increase their emissivity. There are four types of general applications for equipment of this sort: (1) For use in localities in which high ambient temperatures are liable to be encountered occasionally. In such cases, auxiliary air equipment may be used during these unusual warm periods to secure the added ventilation required. (2) To take care of occasional peaks in loading; for example, a transformer may be loaded within its rating 360 days of the year, but be required to carry 25 or 30 percent overload for the other five days. The auxiliary forced air-blast equipment may be used to carry the additional load during the peaks. (3) As a means of providing spare capacity to be used in case of emergency. (4) For use with very large transformers, where lack of space on the tank precludes mounting the necessary number of radiators for self-cooling, without making the case unusually large.

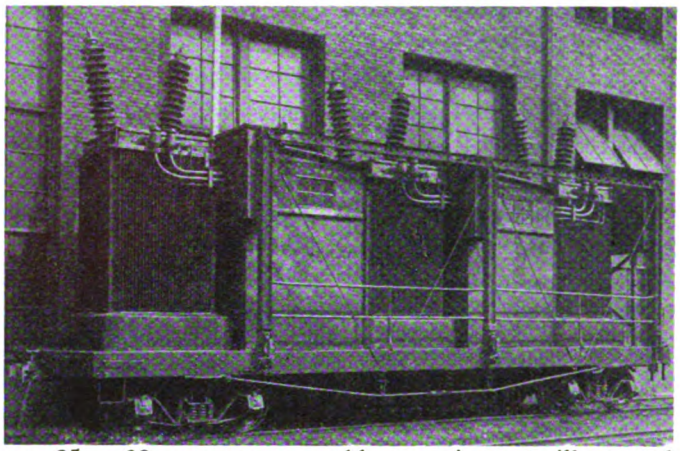

FIG. 1—A PORTABLE SUBSTATION

This is an early application of forced air-blast equipment to a transformer with a corrugated tank. The rating of this substation is increased from 1000 kv-a to 1333 kv-a by an air-blast on the cooling surfaces.

### TYPES OF EQUIPMENT AVAILABLE

One of the earliest applications of auxiliary air-blast equipment, illustrated in Fig. 1, was applied to the corrugated tank of a 1000 kv-a transformer used in a portable substation. Ducts around the base of the transformer deflected the air from a single blower against the radiating surfaces. With this added cooling 1333 kv-a could be obtained from this unit. Another early installation, Fig. 2, used this type of construc-

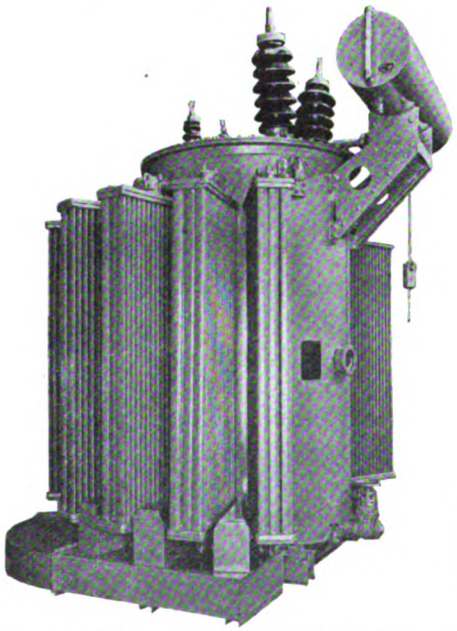

FIG. 2—ONE OF THE FIRST APPLICATIONS OF AN AUXILIARY AIR-BLAST TO RADIATOR TYPE TRANSFORMERS

This is rated at 5000 kv-a, single-phase, 36 610 to 16 500 volts, 50 cycles—6250 kv-a with air-blast.

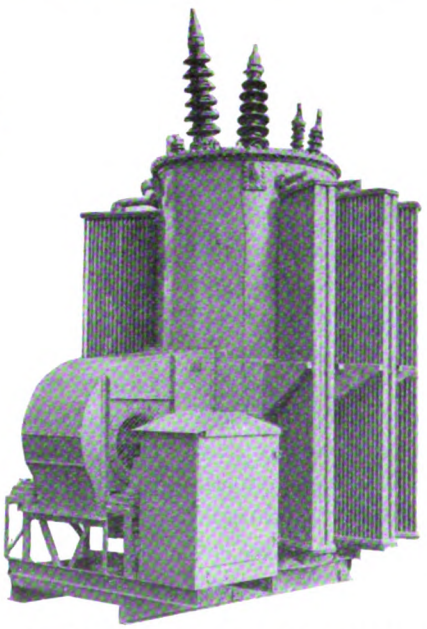

FIG. 3—A MODERN AUXILIARY AIR-BLAST EQUIPMENT

Using a single blower per transformer. This is a 10 000 kv-a, single-phase, 60 cycles, 76 200 H.V., 50 800 M.V., 13 800 L.V.

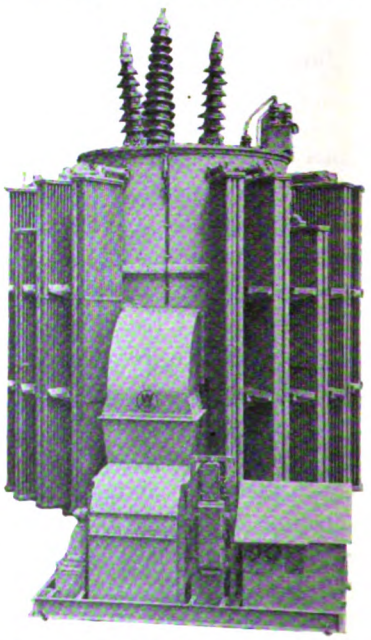

FIG. 4—THE LARGEST TRANSFORMER SO FAR PROVIDED WITH AUXILIARY AIR-BLAST EQUIPMENT

This is a 33 000 kv-a, single-phase, 50 cycle, 127 000 to 16 500 volts unit.

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tion to direct air over the tubes of a radiator-type, 5000 kv-a transformer to increase the rating to 6250 kv-a.

More modern equipment is illustrated in Fig. 3. In this case a single blower is used per transformer. Air from the blower is conducted to one or more sets

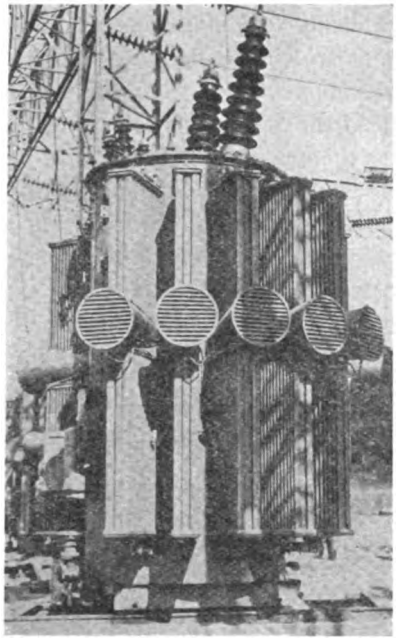

FIG. 5—A TRANSFORMER PROVIDED WITH INDIVIDUAL BLOWERS FOR EACH RADIATOR

This transformer is rated at 6667 kv-a, single-phase, 60 cycles, 76 200 to 14 420 volts.

of air deflectors on the radiators through a duct, which is usually welded to the tank behind the radiators. Automatic control is provided to make the air-blast equipment immediately effective, as soon as a safe temperature for self-cooling is exceeded. Another illustration of a large transformer provided with auxiliary air-blast equipment is given in Fig. 4. This is the largest transformer so far built with this type of equipment, being rated at 33 000 kv-a, 50 cycles, at 127 000 volts.

All of these larger transformers have been provided with a single blower per transformer. At first glance, one blower per bank, or two blowers per bank, with one as a spare, might appear to be a more economical arrangement. The cost of the special connecting ducts, the additional space involved and reduced flexibility, usually more than offset the apparent saving in blowers.

Recently there has been developed an improved type of auxiliary air-blast equipment which employs individual blowers for each radiator. The transformer in Fig. 5 is supplied with blowers of this type. The unit is shown in cross-section in Fig. 6. A small fan, similar to the common exhaust fan, is mounted in the

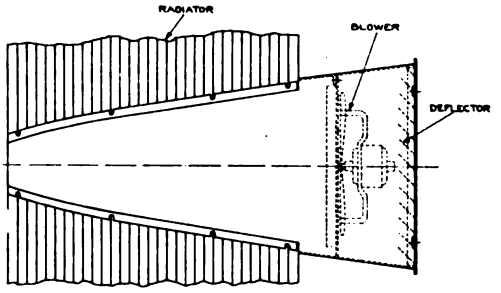


FIG. 6—THE INDIVIDUAL BLOWER UNIT IN CROSS-SECTION

outside end of the sheet-metal air deflector. The small motor driving the fan is totally enclosed, and is impregnated to make it moisture proof. Deflectors in the end permit entrance of air, and deflect rain. A typical installation of transformers thus equipped is shown in Fig. 7. This individual radiator blower equipment has many advantages over the type using a duct system supplied from a single blower. In the first place, the reliability factor is very high. The chance of all blowing units being out of commission at once is very remote. With this system, if one motor or fan gives trouble, a large percentage of the air-blast equipment is still available. Large units may have 10 to 20 or more radiators, so that the loss of one unit reduces the air-blast effectiveness but slightly whereas with the single blower scheme, loss of one motor or trouble with the single blower means complete outage of the air-blast equipment. The radiator blower has the added advantage that spare blowers may be kept on hand at

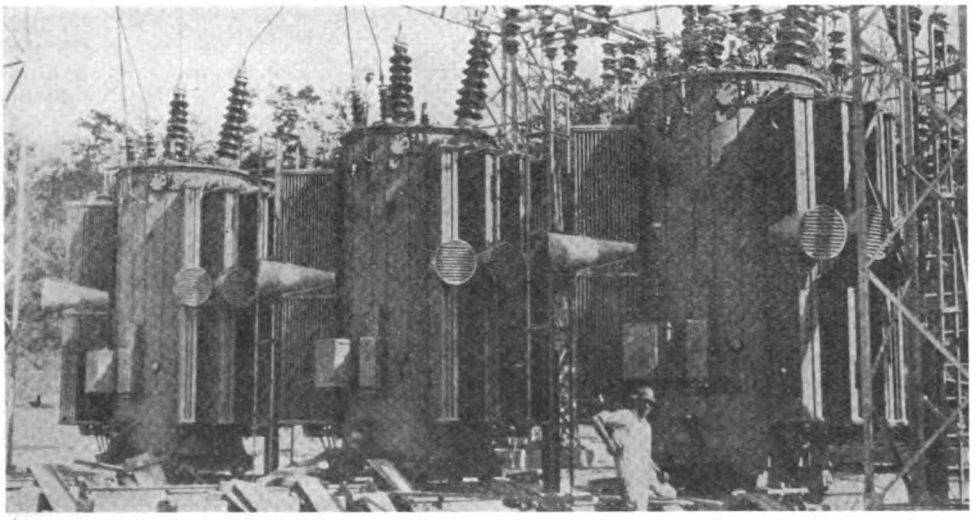

FIG. 7—A TYPICAL INSTALLATION OF AIR-BLAST TRANSFORMERS

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slight cost and may easily be mounted in place if needed.

The maintenance of the individual radiator blowers is also much less, due to the comparatively small amount of steel work to be painted. The duct work involved with the unit blower also makes periodic painting of the radiators more difficult and expensive. The individual blowers may easily be removed and the transformers painted as an ordinary unit. Due to the absence of power loss in the conducting ducts of the unit blower system, the individual radiator blower shows materially lower operating losses—of the order of one-half to one-third that of the unit system.

The individual radiator blower has the added advantage that it can easily be mounted on transformers already installed. By use of this equipment, an inexpensive and efficient means of obtaining increased ratings from old units is readily available. The possible increase in rating naturally depends upon the design of the particular transformer, but will generally be of the order of 25 to 35 percent.

Transformers designed particularly for use with forced air-blast equipment may be arranged for greater

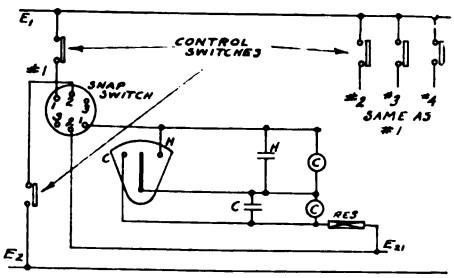


FIG. 8—A SCHEMATIC DIAGRAM OF AUTOMATIC CONTROL FOR AUXILIARY AIR-BLAST EQUIPMENT

overload ratings than this with the auxiliary equipment in use. In order to obtain greater overload capacity, the ratio of copper to iron loss must be made lower. For a given total loss at the self-cooled rating, the copper or load loss may be made lower and the iron or no-load loss made higher than otherwise, so that a given percent increase in load means a lower percent increase in loss, and consequently permits greater overloads to be obtained by means of a given air-blast equipment.

If carried to extremes, this naturally gives a distorted transformer design. Under ordinary conditions it is seldom economical to design for greater than 50 percent overload by means of the air-blast equipment, whereas 35 to 40 percent is a more average figure.

### AUTOMATIC CONTROL

The auxiliary air-blast equipment may easily be arranged for automatic control, starting the blowers as soon as a predetermined oil temperature is reached, and disconnecting them when the equipment is no longer required. An indicating thermometer, Fig. 8, is provided with two contacts, one *Hot* and one *Cold*, which function respectively to start or stop the blower motors. A secondary relay is provided with two contactors and two holding coils which normally are connected in series across the control supply. When the *Hot* contact is made, as the load exceeds the normal self-cooled rating and the temperature of the unit rises, one of the coils is short-circuited, causing full voltage to be applied across the other coil, causing it to close its contactor. When this contactor is closed, a mechanical interlock between the two contactors functions to prevent the other from closing. In closing, the contactor of the secondary relay provides a holding circuit for its own coil and also supplies current to the terminals of the contactor coil of the across-the-line starter, which closes and completes the motor circuit.

The motor and blower will continue to operate until the oil temperature has been reduced to a value which causes the indicating needle of the thermometer to make contact with its *Cold* contact. In that case, the *Hot* coil is short-circuited, causing the *Hot* contactor to open, which in turn causes the contactor of the motor to open,

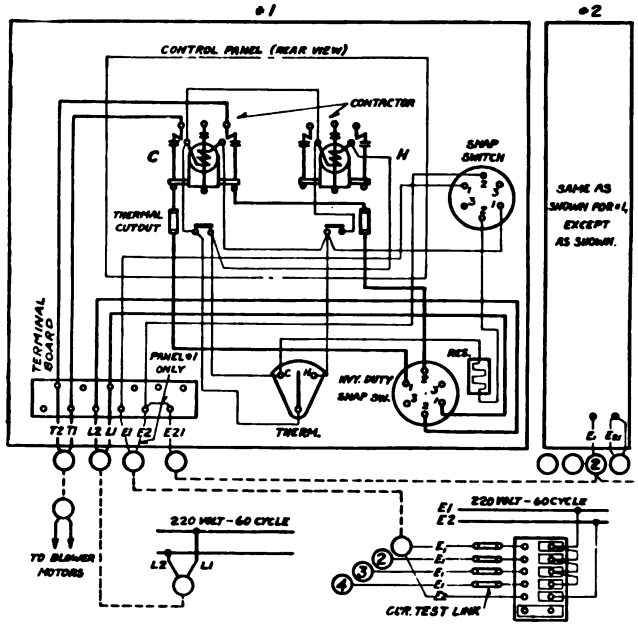


FIG. 9—A TYPICAL WIRING DIAGRAM FOR AUTOMATIC CONTROL OF AUXILIARY AIR-BLAST EQUIPMENT

thereby stopping the motor. The *Hot* thermometer contact is set at a value slightly above the temperature of the hot oil occurring at the maximum straight self-cooled rating. To prevent continuous starting and stopping, the *Cold* contacts are set at a temperature which is several degrees below this maximum oil temperature. Fig. 9 indicates the control diagram of a typical automatic equipment.

### COMPARISON WITH OTHER TYPES OF UNITS

From the operating viewpoint, the completely self-cooled transformer is obviously the most attractive type, and is also the most expensive. At the other extreme is the water-cooled unit, which is the cheapest and requires the most attention. Between these from the standpoint of both cost and maintenance lies the self-cooled, forced air-blast unit. It has the disadvantage of requiring auxiliary apparatus, but on account of its high self-cooled rating, and more desirable cooling fluid, air, has several advantages over the water-cooled unit.

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# A New Type of Turbogenerator Rotor Insulation

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IN general, advance in the design and construction of turbine generators comes through refinements of previous practice rather than through radical changes. In recent years the rating of the largest generators considered possible has increased rapidly. The maximum capacity considered possible is determined by a number of factors, such as rotor stresses and ventilation, stator ventilation and the quality of material available. One of the major problems in building large machines with high rotor peripheral speeds and long rotor coils is the insulation of the rotor windings.

Insulation for turbogenerator rotors must function under a number of adverse conditions. In machines with high peripheral speeds and relatively deep rotor copper the pressure of the copper on the insulation due to centrifugal force may be 4000 lbs. per sq. in. or higher. In rotors of 150 inches active length the rotor coil ends may creep as much as one-sixteenth inch on each end when changing from room to full-load temperature. This creeping action has a destructive effect upon the insulation, since the coils must move with respect to the insulation while under high pressure. At full load the temperature of the copper may be 130 to 150 degrees C., and any insulation used must be able to withstand such temperatures. While the excitation voltage is low (125 or 250 volts) trouble with the insulation may be experienced if proper insulation surface distances are not allowed between the copper and the grounded parts, since dirt carried in by the ventilating air will collect on these creepage surfaces and the leakage current may harm the insulation if the creepage distances are made too small.

The insulation designed for the small rotors with lower peripheral speeds and relatively short coils, as formerly used on all rotors, is applied as follows. Radial slots are machined into the rotor and are lined with U-shaped channels of mica, which extend somewhat beyond the ends of the slots. The rotor coils are then wound, a turn at a time, with mica strips between turns. They are then pressed and baked several times to produce compact coils. A mica strip is placed in the top of the slot, and is covered with a brass strip. The wedges are then driven in over the brass strip. The rotor coil ends are covered with asbestos tape filled with varnish, which is baked on in another baking operation. The rotor is then ready for the high-grade steel retaining rings which hold the rotor coil ends against the action of centrifugal force.

The retaining rings are made with a slight taper to the inner bore and a mica lining is baked in place under pressure on the inside of the ring. The pressure is applied by means of a steel plunger having a taper to correspond to that of the ring. The insulation be-

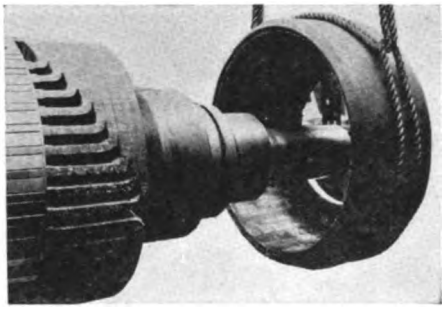

FIG. 1—PLACING ROTOR RETAINING RING IN POSITION
This rotor has the older type of insulation with an asbestos tape on the coil ends and a mica lining in the retaining ring.

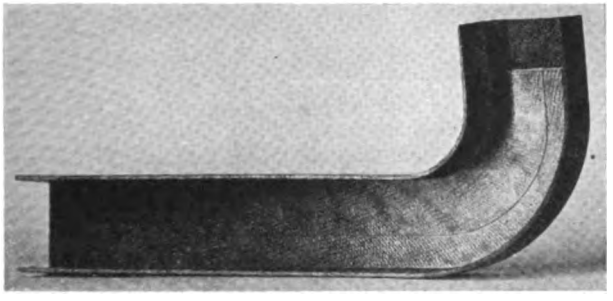

FIG. 2—A MOULDED BAKELIZED ASBESTOS CHANNEL
Note the stepped joint between this channel and the adjacent one.

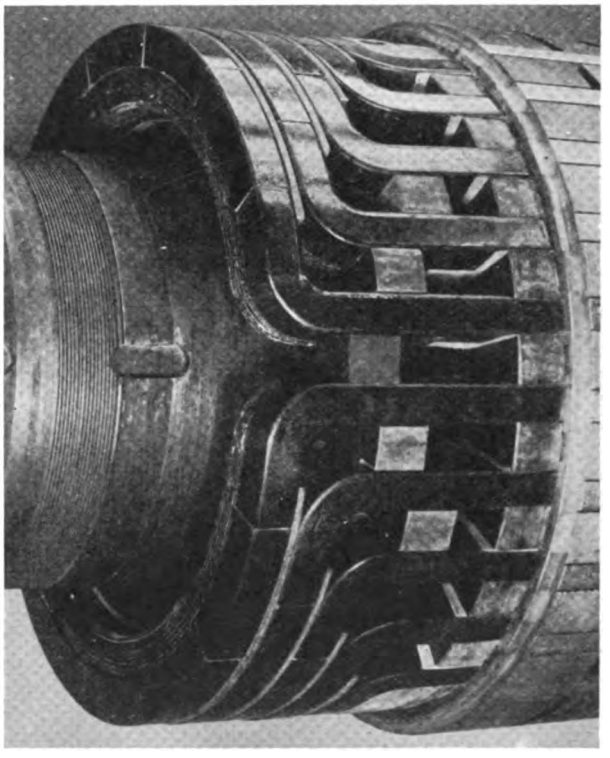

FIG. 3—THE NEW MOULDED INSULATION APPLIED TO A TWO-POLE, 60 CYCLE TURBINE-GENERATOR ROTOR

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tween the rotor coil ends and the retaining ring therefore consists of a layer of asbestos tape over the coils and the mica lining in the ring. The function of the asbestos tape is to keep dirt from getting on the coil ends rather than to act as an insulator. Insulation of this type is shown in Fig. 1.

Early in 1924, work was begun on a new type of insulation for the rotor coil ends of single-phase generators for railway service. The conditions encountered

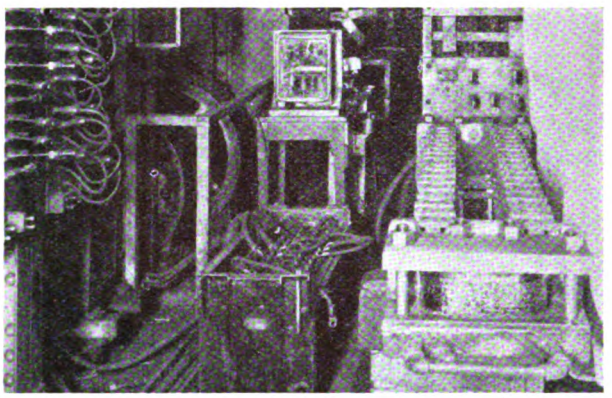

FIG 4—ARRANGEMENT OF TEST APPARATUS FOR TESTING ROTOR INSULATION MATERIALS

The rotor model is in the foreground with the automatic switching equipment and motor-generator set on the left.

in railway service are unusually severe, due to the rapid and frequent changes in load, which cause the rotor coils to expand and contract several times per

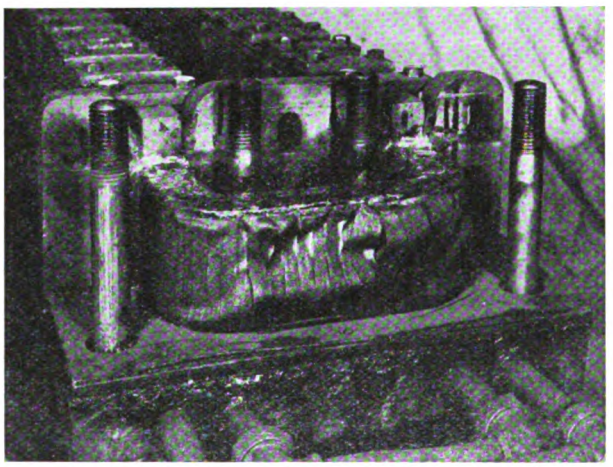

FIG. 5—CONDITION OF ROTOR INSULATION OF OLD TYPE AFTER 350 HEATING AND COOLING CYCLES

The mica insulation of the top plate (removed in this picture) which imitates the insulation of the retaining ring was broken up by the creepage of the coil across the insulation while under high pressure.

hour. Special channel-shaped pieces of bakelized asbestos material and of such a shape as to fit over the top of the rotor coil ends were moulded in steel dies under heat and pressure. The bakelized asbestos material is very tough and resistent to abrasion and heat. One of these channels is shown in Fig. 2, and an application of these channels to a two-pole, sixty-cycle generator is shown in Fig. 3. Where these channels are used, the retaining rings are lined with the same bakelized asbestos material. The surface of the coil ends next the shaft are left open to the air to obtain better cooling. Due to the large creepage surfaces presented by the moulded channels, the presence of dirt in the end windings would not affect the insulation. The channels are made up in several sections so that they can readily be assembled on the coils, and stepped joints are made between sections. Considerable experimental work was required before the channels could be moulded satisfactorily, since their peculiar shapes, and the accuracy in dimensions to which they had to be held, made their manufacture difficult.

Usually the success of new types of insulation can only be determined after a number of machines have been operating for several years. In this case however, it was decided to build a model which would reproduce the conditions under which the moulded insulation would have to work, and run tests to determine the relative life of the new insulation as compared to the old. A special water-cooled casting was made with two slots, each 100 inches long, machined in it to receive

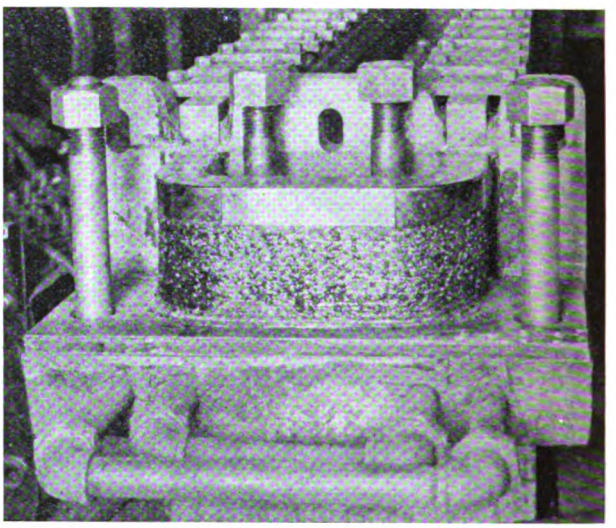

FIG. 6—CONDITION OF NEW MOULDED ROTOR CHANNELS AFTER 1500 CYCLES OF HEATING AND COOLING

Showing practically no wear on channels. The insulation of the top plate was also practically undisturbed.

a coil similar to a rotor coil and insulated in the regular way in the slot portion, as shown in Fig. 4. The coil was held in the slots by clamps. The insulated coil ends were bolted down to projecting parts of the casting by means of two plates, which were insulated on the side next the coil, similar to the insulation in the retaining rings. Pressure on the coil ends, corresponding to that due to centrifugal force, was produced by tightening the four holding-down bolts on each end. The tension in the bolts was determined by measuring their elongation under tension. An automatic switching device was arranged to circulate direct current through the coil for 15 minutes, by the end of which time the coil had reached a temperature of about 150 degrees C by resistance. The current was then automatically cut off and the coil allowed to cool for 45 minutes, after which the cycle was repeated again. It was thus possible to

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expand and contract the coil once every hour under conditions of pressure and temperature similar to those occurring in actual machines.

Comparative tests of the old and new insulation were made with this model. With a pressure of 4000 pounds per sq. in. of copper surface on the top of the coil ends, the old type of insulation with asbestos tape over the coil ends and a mica lining for the top plates was practically destroyed after 350 cycles, while the moulded insulation showed little signs of wear after 1500 cycles. The condition of the insulation in the two tests is shown in Figs. 5 and 6. Assuming that a large turbine generator is shut down once a week, the test on the moulded insulation would be equivalent to 30 years service.

The above tests were made under conditions considerably more severe than would be expected in service. It should be noted that the older type of insulation has stood up satisfactorily in service during the twelve years it has been used, and this type of insulation will be continued on the smaller turbine generators. The new insulation is being applied to new large generators. The development of this new and better type of rotor insulation improves the performance of the large machines now built, and permits the construction of still larger turbine generators.

# Practical Considerations Affecting Quick-Response Excitation for Salient Pole Machines

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MUCH work has been done to find some practical method of increasing machine stability without radically altering the design of the machine. It has been established as a result of analytical work and tests[1] that the pull-out characteristics of a system with synchronous machines at both ends could be considerably increased if the field currents of the synchronous machines were built up rapidly. To obtain this result it was necessary to use an exciter having a higher maximum voltage than previously used and having a very rapid rate of building up of its voltage when the voltage regulator contacts close.

Previous to the use of quick-response excitation, the only practical method of increasing stability was to design special machines having high short-circuit ratios and low leakage reactance. Such a design, however, is usually expensive. The feasibility of using quick-response excitation was only recently recognized[2], but interest in this scheme spread rapidly, and more and more operating companies came to recognize its possibilities. Although it may not be the ideal method of increasing stability in that it does not remove the cause of instability, nevertheless it is the most practicable method available at the present time.

It is the purpose of this article to analyze the more important factors entering into the design and application of quick response excitation systems and their effect upon the synchronous machines.

There are several factors which influence the rate of response obtainable from a given exciter, all of which are limited by practical design. The rate at which the exciter terminal voltage builds up is dependent upon the rate at which the current in the exciter field can be increased. Therefore, a self-excited exciter is particularly unsuitable for quick response, because the terminal voltage and the rate of increase are mutually dependent. For this reason a pilot exciter is used to furnish excitation for the exciter field.

When a voltage is applied to any inductive circuit, the rate at which the current will build up is determined by the time constant of that circuit or the ratio of $L/R$. The expression for the rate of building up of current is given by the following equation:—

$$L\frac{di}{dt} = e - Ri \qquad (1)$$

where $L$ is the inductance, $e$ the applied voltage, $R$ the resistance, and $di/dt$ the rate of change of the current. This expression is a differential equation having a constant and a variable term, the solution being:—

$$\frac{di}{-\frac{e}{R} + i} = -dt\,\frac{R}{L} \qquad (2)$$

$$\log_\epsilon\left(i - \frac{e}{R}\right) = -\frac{R}{L}\,t \qquad (3)$$

$$i = \frac{e}{R} + \left(I_0 - \frac{e}{R}\right)\epsilon^{-\frac{R}{L}t} \qquad (4)$$

Where $I_0$ is the initial current. When $t = 0$, for the steady state condition.

$$i = \frac{e}{R} \qquad (5)$$

The time constant of the circuit is $L/R$ so it is apparent that anything that reduces the inductance will increase the rate of building up the field current. The inductance of the field circuit depends upon the flux linkages per ampere. To decrease the inductance it is necessary to decrease the flux or the number of turns. The minimum number of turns per pole is usually fixed for any particular machine by regulator limitations and

[1] See an article on "Quick Response Excitation for Alternating-Current Synchronous Machinery" by C. A. Powell in the JOURNAL for April, 1927, p. 157.

[2] See discussion by C. F. Wagner, Midwinter Convention, Feb. 10, 1925 in the *Journal of the A.I.E.E.* for July, 1925, p. 769.

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practical design. The flux per pole cannot be varied over a wide range, so little is gained in reducing inductance by this means.

Increasing the rotational speed obviously will increase the response of any exciter since the generated voltage is a direct function of the air-gap flux and the speed. Hence for any given value of air-gap flux, a higher speed will produce a higher voltage, and still the inductance will not have changed. The most logical and effective method of reducing the inductance is to divide the field circuit into a number of parallel paths. Equation (4) shows that an increase in the voltage applied to the field will increase the rate of building up the exciter terminal voltage. This in effect is exactly what happens when the field is divided into parallel paths, but the added advantage is that the same result is obtained with a lower voltage pilot exciter than if only one field circuit were used. Furthermore the commutation requirements of the pilot exciter are not nearly so severe. The chief objection to the use of high applied voltage to the exciter field is the abnormal requirements imposed upon the voltage regulator. Sufficient resistance must be inserted in the field circuit to allow the exciter to operate at the slip ring voltage of the main generator, which means that the regulator contacts must shunt out this resistance when closed. There are more difficulties encountered in the design of quick-response excitation systems to keep within the limitations imposed by the regulator than by any other factor.

Response curves for a normally-designed, 1000 r.p.m., 500 volt exciter, separately-excited from a 250-volt source are shown in Fig. 1. The normal slip-ring voltage of the generator is 125 volts, so the exciter is assumed to build up from this voltage. Sufficient resistance is placed in the field circuit to prevent the voltage from building up above a maximum of 500 volts when the regulator contracts close and stay closed. Curves 1,

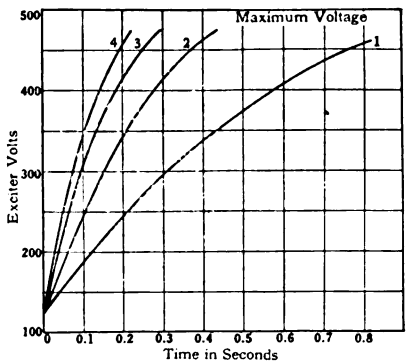


FIG. 1—RESPONSE OF AN EXCITER WITH DIFFERENT NUMBERS OF PARALLEL FIELD CIRCUITS

2, 3 and 4 give the response obtainable when the field circuit is divided into 1, 2, 3 and 4 parallel circuits respectively. The effect of increasing the number of parallel paths is clearly indicated. Curve 2 is exactly the same curve as would be obtained if only one circuit were used and 500 volts used to excite the field, instead of two circuits with 250 volt excitation. Fig. 2 is taken from the curves in Fig. 1, and shows the time required to build up the voltage from 125 to 400 with different numbers of parallel circuits. It can be seen that two circuits require half the time, and four circuits one-fourth the time that one circuit does.

Obviously the rate of building up the exciter field current and hence the armature voltage, is dependent upon the excess voltage applied to the field, so if a sufficiently high voltage is applied, practically any response can be obtained. Usually it is not considered good engineering to force the field with an abnormally high voltage, when what little is gained by so doing is offset by complications in the design of the voltage regulator

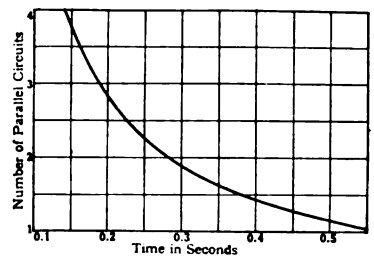


FIG. 2—TIME REQUIRED FOR AN EXCITER TO BUILD UP TO 400 VOLTS

Another factor that must be considered is the effect of eddy currents. When the voltage and current are building up, the flux is increasing. As a result eddy currents are induced in the pole faces that tend to prevent the flux from changing and hence decrease the rate of building up the voltage. The effect of the eddy currents can be minimized by laminating the poles and yoke.

## GENERATOR CHARACTERISTICS

When a generator is running on open circuit the terminal and air-gap voltages are the same. If the generator is short-circuited the resulting current that flows is less than would be indicated by dividing the original air-gap voltage by the leakage reactance. The air-gap voltage is that produced by the flux that passes across the air-gap to the armature. This reduction in short-circuit current is caused by the air-gap flux being reduced under the demagnetizing action of the armature current. The air-gap voltage of the generator is directly proportional to the air-gap flux, and if the flux remained constant during the transient the induced voltage would also remain constant. The demagnetizing armature ampere-turns, however, reduce this flux, and the initial current that flows is determined by the air-gap voltage at its initial reduced value. A clearer conception of the method of analysis is obtained from Fig. 3. The no-load saturation curve is the voltage produced only by the air-gap flux at various field currents. The no-load voltages are directly proportional to the air-gap flux, but the air-gap flux is not proportional to the field current, since a greater number of ampere-turns are required for a given increase of flux as the magnetic circuit becomes saturated. The total flux through the magnetic circuit consists of the air-gap flux and the pole leakage flux. The pole leakage can be divided into two principal parts, the pole tip and side leakage. The air-

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gap flux and the pole-tip leakage flux link all the turns of the field poles, but the side leakage links only a portion of the turns. The inductance of the field circuit is determined by the flux that links all the turns of the field circuit. The pole leakage flux for all practical purposes, can be considered as being directly proportional to the field current. On this basis then the total flux curve can be constructed by adding the pole-leakage to the air-gap flux, after making correction for the pole side leakage which does not link all the turns, as shown in Fig. 3. The field leakage flux is expressed as a percentage of voltage, hence can be added directly to the no-load saturation curve.

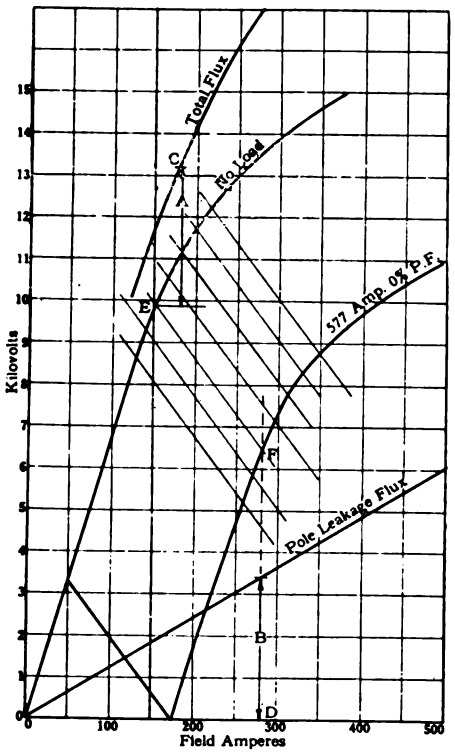


FIG. 3—THE SATURATION AND FLUX CURVES OF A VERTICAL, WATER WHEEL GENERATOR OF NORMAL DESIGN

Which has a short-circuit ratio of 1.0 and is rated at 11 000 kv-a, three-phase, 50 cycles, 11 000 volts, and 150 r.p.m.

If the generator is short-circuited or the load suddenly increased, the immediate result is to decrease the air-gap flux and increase the current in the field circuit. The total flux linkages of the field circuit before the change in load is $N\phi_T = N\ (\phi_{a_1} + \phi_{x_1})$, where $\phi_T$ is the flux linking all the turns, $\phi_{a_1}$ the air-gap flux and $\phi_{x_1}$ the leakage flux before the disturbance occurred. The flux linkages with any circuit cannot change instantly, and hence if $\phi_{a_1}$ is to decrease to some value $\phi_{a_2}$ there must be a corresponding increase in $\phi_{x_1}$. To increase $\phi_{x_1}$, the field current must increase from its initial value $I_{f_1}$ to some new value $I_{f_2}$. The increased field current is caused to flow by the induced voltage $-N\frac{d\phi_T}{dt}$ in the field circuit. The oscillogram, Fig. 4, shows the instantaneous increase of main machine field current and decrease of air-gap voltage before there is any change in the exciter voltage.

From this explanation of what takes place in a generator during transient conditions, a simple method of determining the initial drop in the air-gap voltage and the value to which the field current will increase, due to the induced voltage in the field circuit, readily presents itself. Since during the first instant of the transient the total flux linkages, and hence the total flux, do not change, the total flux curve can be used as a starting point. Assume that the generator is running on open circuit at normal voltage, and a load of 100 percent zero power-factor lagging is suddenly applied. The total flux for no-load normal voltage is that on the total flux curve at *C*. If the air-gap flux decreases, the pole leakage flux must increase in order that the total flux be the same. There must be one point on the no-load saturation curve and one on the zero power-factor curve, located at opposite ends of the hypotenuse of the Potier triangle, which will satisfy this condition. To locate these points, find a distance *B* between the base line and the pole leakage flux line. Step off this distance vertically downward from the point *C* on the total flux curve corresponding to normal no-load voltage, so that its horizontal projection *A* strikes a point *E* at the apex of the Potier triangle corresponding to the point *F* on the zero power-factor curve at the field current value *D*. It should be noted that points *E* and *F* correspond to each other on the hypotenuse of the Potier triangle. For any given condition there are only two points that can be found that are so related. Since the leakage flux has increased to point *D* the field current also must have increased to this point, and the air-gap voltage has decreased to *E*, but the total flux remains the same for the first instant. This method of determining the initial drop of the air-gap voltage gives a slightly greater decrease than actual tests would indicate, due to the fact that the affect of eddy-currents is neglected. As pointed out in the case of an exciter, when the flux changes rapidly eddy-currents are induced in the poles and yoke which tend to prevent the flux from changing.

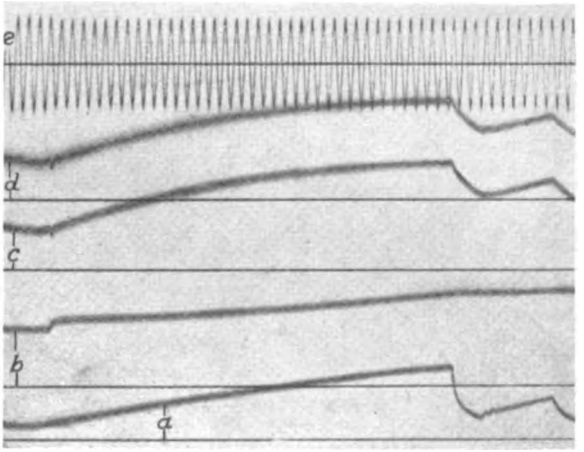


FIG. 4—OSCILLOGRAM SHOWING THE BUILDING UP OF THE EXCITER AND MAIN FIELDS

Curve *a* is exciter field current; *b*, main field current; *c*, exciter voltage; *d*, main field voltage; *e*, generator voltage.

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The amount of the initial drop in the air-gap voltage due to the redistribution of the total flux under the influence of the armature demagnetizing ampere-turns is an inherent characteristic of the particular design, and the value cannot be reduced without changing

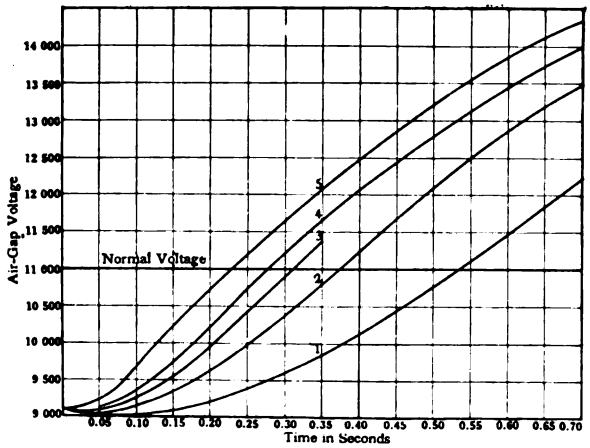


FIG. 5 -RESPONSE CURVES FOR A GENERATOR WHEN RUNNING ON OPEN CIRCUIT AND 100 PERCENT LOAD AT ZERO PERCENT POWER-FACTOR LAGGING IS SUDDENLY APPLIED

The generator is rated at 11 000 kv-a, 11 000 volts, 150 r.p.m. and has a short-circuit ratio of 0.85.

Curve 1 is with an exciter response of 500 volts per second; curve 2, 1000 v.p.s.; curve 3, 1500 v.p.s.; curve 4, 2000 v.p.s.; curve 5, 4000 v.p.s.

the design of the machine. No matter how high the rate of response of the exciter, the initial reduction in internal voltage will be the same, as the drop is almost instantaneous and the regulator contacts cannot close quickly enough to allow the exciter voltage to build up. Furthermore, even though the main field might be forced by a very high applied voltage the effect would be entirely negligible, since the main field is so highly induc-

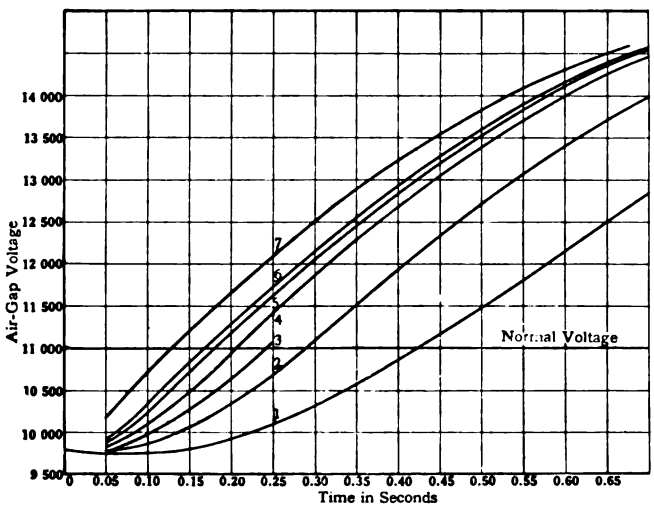


FIG. 6—RESPONSE CURVES FOR A GENERATOR WITH A SHORT-CIRCUIT RATIO OF 1.0

Curve 1 is with an exciter response of 500 volts per second; curve 2, 1000 v.p.s; curve 3, 1500 v.p.s.; curve 4, 2000 v.p.s.; curve 5, 3000 v.p.s.; curve 6, 4000 v.p.s.; curve 7, infinite v.p.s.

tive that the rate of building up of the main field current lags the building up of the applied voltage. The initial drop under any assumed change of load can be reduced by increasing the short-circuit ratio. The short-circuit ratio is a measure of the relative strength of the field to the armature. In a high short-circuit ratio generator, a given armature current will not produce as great a demagnetizing effect as in a low short-circuit ratio generator. Decreasing the short-circuit ratio of any machine means moving the air-gap line and no-load saturation curve back, thus increasing the initial drop. It is evident from Fig. 3 that the pole leakage flux is an important factor. Decreasing the pole leakage flux de-

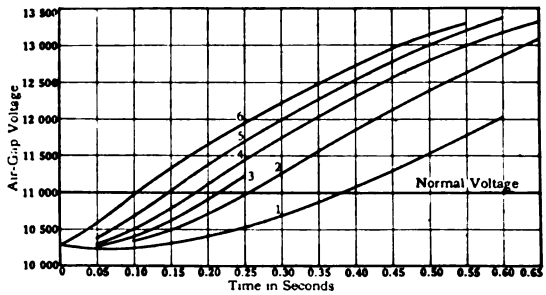


FIG. 7—RESPONSE CURVES FOR A GENERATOR WITH A SHORT-CIRCUIT RATIO OF 1.65

Curve 1 is with an exciter response of 500 volts per second; curve 2, 1000 v.p.s.; curve 3, 1500 v.p.s.; curve 4, 2000 v.p.s.; curve 5, 4000 v.p.s.; curve 6, infinite v.p.s

creases the initial drop in air-gap voltage, but field design limitations prevent any radical change being made to reduce the pole leakage.

The effect of the reduction of air-gap flux on the stability of the system to which the generator is connected can be minimized if the flux can be brought back to normal and increased above normal in a very short time. The synchronizing power available for holding a system in step is a function of the square of the air-gap voltage. The natural period of oscillation of large power systems lies between 1 and 1.5 seconds. Since the rotor position cannot change to any considerable extent in the short time required to restore the air-gap flux, the initial decrease in the flux is not the most important consideration.

## GENERATOR RESPONSE

The effect of exciter speed of response on the speed of response of a generator is shown by the curves of

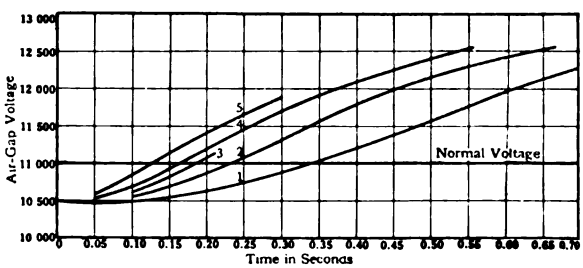


FIG. 8—RESPONSE CURVES FOR A GENERATOR WITH A SHORT-CIRCUIT RATIO OF 2.0

Curve 1 with an exciter response of 500 volts per second; curve 2, 1000 v.p.s.; curve 3, 1500 v.p.s.; curve 4, 2000 v.p.s.; curve 5, 4000 v.p.s.

air-gap voltage vs. time in Figs. 5, 6, 7, 8 for generators having short-circuit ratios of 0.85, 1.0, 1.65 and 2 respectively, with different speeds of exciter response. An entirely arbitrary basis was used for the calculations. It is assumed that the generators are running on open circuit, and a 100 percent load at zero power-factor lagging is suddenly applied. This means that the load

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is applied when the machine is operating at a lower value of excitation, and hence with a lower air-gap voltage, than would be found under actual operating conditions. The basis for calculating such curves should exactly simulate all limiting operating conditions. In general, it is not possible to find a single basis that will do this; consequently, the one employed was chosen because it is representative, so far as the effects of the

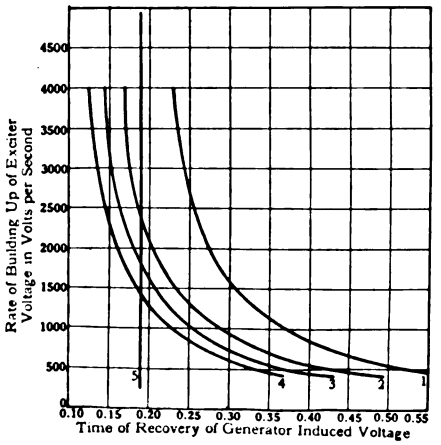


FIG 9—THE VARIATION OF TIME OF RECOVERY OF GENERATOR VOLTAGE AND RATE OF INCREASE OF EXCITER VOLTAGE

For different short-circuit ratios: curve 1, 0.85; curve 2, 1.0; curve 3, 1.65; curve 4, 2.0; and curve 5 the limiting value of time of recovery of generator with short-circuit ratio of 0.85.

various factors are concerned and, because of these considerations, is more readily understood than would be the case if a less simple basis were selected.

Except for the short-circuit ratios, the generators of Figs. 5, 6, 7 and 8 are similar and the slip ring voltages about the same. The exciter in each case builds up from 115 to 500 volts.

The rate of building up the generator field current is determined by equation (4) exactly as for the exciter field current, and the same discussion applies. It should be noted that the inductance $L$ is a variable, depending

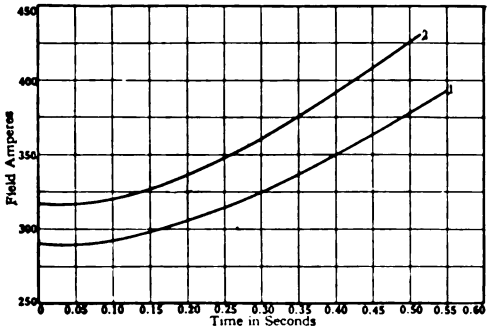


FIG 10—THE BUILDING UP OF MAIN FIELD CURRENT WHEN THE EXCITER VOLTAGE IS INCREASING

Curve 1 is for a generator short-circuit ratio of 1.65. Curve 2 is for a generator short-circuit ratio of 2.00.

upon the saturation of the magnetic circuit. If the saturation of the circuit were neglected the inductance would remain constant throughout the range of variation of the main field current. The inductance of the field circuit must be calculated, and a step-by-step solution employed, to determine the rate of building up of the main field current under the influence of the increasing exciter voltage. The change of the induced voltage of the generator can be determined as follows:—

$$e - iR = N \frac{d\phi_T}{dt} 10^{-8} \quad \ldots\ldots (6)$$

$$e = iR = L \frac{di}{dt} \quad \ldots\ldots (7)$$

$$\phi_T = \phi_{a1} \frac{E_1}{E_n} + \phi_x \frac{I_{f1}}{I_{fn}} \quad \ldots\ldots (8)$$

$$\frac{d\phi_T}{dt} = \frac{\phi_{a1}}{E_n} \frac{dE}{dt} + \frac{\phi_x}{I_{fn}} \frac{di}{dt} \quad \ldots\ldots (9)$$

Substituting—

$$\frac{e-iR}{N} 10^8 = \frac{\phi_{a1}}{E_n} \frac{dE}{dt} + \frac{\phi_x}{I_{fn}} \frac{e-iR}{L} \quad \ldots\ldots (10)$$

$$\frac{dE}{dt} = \frac{En}{\phi_{a1}} \left[ e - iR \left( \frac{10^8}{N} - \frac{\phi_x}{LI_{fn}} \right) \right] \quad \ldots\ldots (11)$$

Where, $e$ = Exciter voltage. $R$ = Field resistance. $N$ = Number of turns in field circuit. $L$ = Total inductance of the field circuit. $\phi_T$ = Total flux. $E_n$ = Normal voltage at no load. $\phi_x$ = Leakage flux at normal voltage. $i$ = Instantaneous value of field current. $I_{fn}$ = Field current at normal voltage. $I_{f1}$ = Field current corresponding to $E_1$. $E_1$ = Any value of induced voltage. $\phi_{a1}$ = Air-gap flux at normal voltage.

As the total flux increases, the flux linkages per ampere decrease, and it can be seen that the decreasing inductance tends to increase the rate of building up main field current and decrease the rate of building up the generator voltage.

Reference to Figs. 5, 6, 7 and 8 shows that for a given maximum exciter voltage, the response of the generator voltage is not directly proportional to the rate

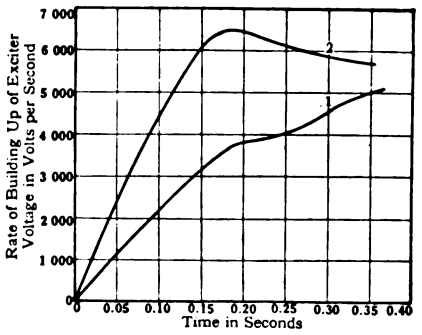


FIG 11—GENERATOR RESPONSE RATIO WHEN MAIN FIELD IS CHANGING AS IN FIG. 10

Curve 1 is for a generator short-circuit ratio of 2.0
Curve 2 is for a generator short-circuit ratio of 1.65.

of building up of exciter voltage. This fact was early recognized, and for that reason the response of the exciter is not used as a criterion of generator response.

The relation between time of recovery of the air-gap voltage and the rate of building up the exciter voltage for machines of different short-circuit ratios is clearly shown by Fig. 9. These curves are derived from the generator response curves. The time required to bring the air-gap voltage back to its original value after the load is applied, is plotted against the rate of building up exciter voltage which produces this rate of response. The examples shown are not in any way special cases, and similar results would be obtained on any type of synchronous machine. In general, therefore, for any maximum exciter voltage, the response of the generator is some function of the rate of response, and above a certain rate, little increase in the generator response can be obtained by further increase of the

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rate of exciter response. The knee of the curves for the generators of various short-circuit ratios in Fig. 9 is at approximately 1500 volts per second exciter response. With a ratio of maximum to normal exciter voltage of approximately 5 to 1, the fallacy in increasing the rate of response from 1500 to 3000 or 4000 volts per second is evident, as no appreciable increase in generator response would be obtained. If the generator response is to be further increased, the only practical method is to increase the maximum exciter voltage or decrease the slip-ring voltage. The factor which determines the rate of building up the field is the ratio of maximum voltage to the normal slip-ring voltage, and not the actual value of the maximum voltage. If curves similar to those of Fig. 9 are calculated for a higher maximum voltage, they will be found to have the same general characteristics, and a point will be reached beyond which no gain is obtained by increasing the exciter response. It will be noted that curve 1, Fig. 9, approches its limiting value as an asymptote. The limiting value is the time of recovery of air-gap voltage when the exciter builds up to its maximum voltage in zero time.

In Fig. 10 is shown the building up of the main field current for generators having short-circuit ratios of 1.65 and 2.0. The field currents do not start from the same point, but from the value reached due to the voltage induced in the field circuit by the change of flux at the instant the load is applied. It is evident from a comparison of the slopes of the two curves that the current in the field of the generator with short-circuit ratio of 2.0 increases at a greater rate than that in the generator with lower short-circuit ratio. The curves in Fig. 11 show the generator response as a rate when the main field current is changing as in Fig. 10. The curves are plotted in volts per second against time, that is, $dE/dt$ against $t$, thus giving at any instant the rate of change of voltage. It will be noted that the rate is higher with the short-circuit ratio of 1.65 than with the ratio of 2. This at first does not appear con-

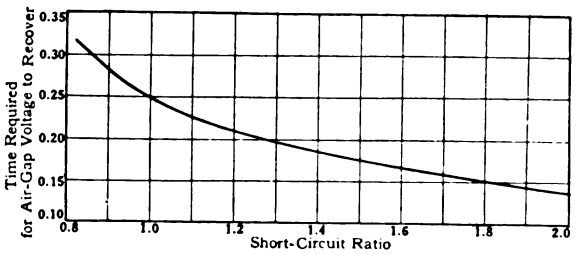


FIG. 12—TIME REQUIRED TO BRING GENERATOR AIR-GAP VOLTAGE TO NORMAL

sistent, since the reverse is true of the rate of increase of main field current. A consideration of equations (4) and (11), however, will indicate that this is probably to be ascribed to the decrease of the inductance, as the magnetic circuit becomes saturated. The machine with the short-circuit ratio of 2 is operated with a higher saturation than the other. As the circuit becomes saturated the inductance decreases, thus reducing the time constant $L/R$, and producing a more rapid increase in the rate of building up. Since the high short-circuit ratio machine has a lower inductance, the rate of change of current is greater, of voltage is less.

The curves in Fig. 13 show the effect ot saturation on the building up of kv-a of a synchronous condenser. Curve 1 was calculated neglecting saturation and curve 2 including it. Great care must be exercised

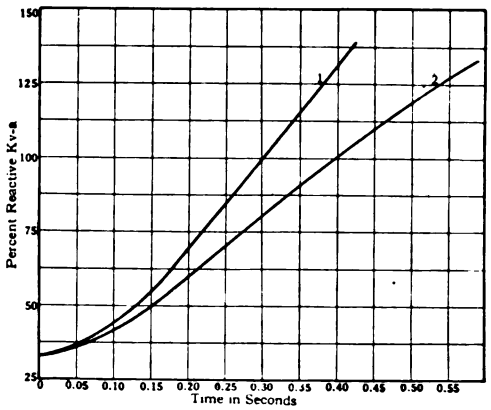


FIG. 13—CALCULATED RATE OF BUILDING UP OF KV-A

in making such calculations, as the neglect of certain factors simplifies the problem, but is less accurate.

In Fig. 12, time of recovery of the air-gap voltage is plotted against short-circuit ratio. By time of recovery is meant the time required to bring the air-gap voltage back to normal after the initial drop. The recovery is based on an exciter speed of response of 1500 volts per second, building up to a maximum of approximately five times normal slip-ring voltage. It can be seen that the time of recovery is not directly proportional to the short-circuit ratio, and that beyond a certain value the gain obtained by increasing this ratio is relatively small. The shorter time of recovery for the high short-circuit ratio machines is due, not to a higher rate of response, but to a smaller initial drop. The lower short-circuit ratio machines are inherently better suited to the application of quick response excitation. The field of a high short-circuit ratio machine, being strong with respect to the armature, is necessarily more sluggish.

In considering any means of improving system stability it is important not to neglect the effect of leakage reactance of the synchronous machines. It is useful to consider the leakage reactance of generators connected by a transmission line as part of the line reactance. A low leakage reactance permits more synchronizing power to flow per unit angle of displacement of the rotor position, and hence tends to improve stability.

In conclusion it should be pointed out that quick-response excitation, like all other remedies, must be properly applied to be effective. The quick recovery of air-gap voltage at one part of a system will not necessarily prevent loss of synchronism. Since the pull-out value of a system is proportional to the product of the sending and receiving-end induced voltages, maintaining the voltage at one end and not at the other may not help the system to any appreciable extent. Moreover, sufficient corrective kv-a must be available.

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# The Work of Oliver Heaviside (Concl.*)

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Consulting Engineer,
Boston, Mass.

THE next problem before Heaviside lay in suggesting means for realizing the distortionless circuit in practice. For this purpose it is necessary to secure a large amount of inductance without undue increase in the resistance. To secure this inductance he suggested two courses. In "Electrical Papers" Vol. II, 1892, he proposed taking "the finest iron filings (siftings) and mixing them with a black wax" an idea to which he continually reverted in later years. In "Electromagnetic Theory" Vol. I, p. 443, 1893, he states: "The above considerations show that if iron be introduced to increase the inductance it should not be in the main circuit, but external to it. There are, then, two principal ways suggested: First, to load the dielectric with finely-divided iron, and plenty of it. This is very attractive from the theoretical point of view, as it results in the production of a strongly magnetic insulator, which is practically homogenous in bulk, being a sort of non-conducting iron of low permeability. In this way $L$, as compared with the same without the iron, may be multiplied greatly." Though it has taken many years to realize the success of Heaviside's "ironic circuit" as he used to call it facetiously, this has at last been done.[11]

Another method for the realization of a distortionless circuit which Heaviside proposed was described by him as follows: "Another indirect way is this. Instead of trying to get large uniformly spread inductance, try to get a large average inductance. Or, combine the two and have large distributed inductance together with inductance in isolated lumps. This means the insertion of inductance coils at intervals in the main circuit. That is to say, just as the effect of uniform leakage may be imitated by leakage concentrated at distinct points, so we should try to imitate the inertial effect of uniform inductance by concentrating the inductance at distinct points. The more points the better, of course. Say $m$ coils in the length l, or $2m$ coils of the same total inductance, and therefore each of half the inductance; or $mn$ coils, each of one $n$th the inductance of the first. The electrical difficulty here is that inductance coils have resistance as well, and if this be too great the remedy is worse than the disease. But it would seem to be sufficient if the effect of the extra resistance be of minor importance compared with the effect of the increased inductance. This means using coils of low resistance and the largest possible time-constants. For, suppose four ohms per kilometer is the natural resistance, and there be one coil per kilometer having a resistance of one ohm. This will raise the average resistance to five ohms per kilometer; and if the time-constant be big enough, the extra inductance may far more than nullify the resistance evil. The same reasoning applies to coils at greater intervals, only of course, in a more imperfect manner. To get large inductance with small resistance, or, more generally, to make coils having large time-constants requires the use of plenty of copper to get the conductance, and plenty of iron to get the inductance, employing a properly closed magnetic circuit properly divided to prevent extra resistance and cancellation of the increased inductance. This plan does not belong to the category of those mentioned before, which a moment's consideration showed to be worse than useless. It is a straightforward way of increasing $L$ largely without too much increase of resistance, and may be worth working out and development. But I should add that there is, so far, no direct evidence of the beneficial action of inductance brought in in this way."

The last sentence here quoted, written toward the end of 1893, indicates that the suggestion to try inductance coils in "lumps" about one per kilometer had not been tried at that time. Heaviside had satisfied himself that such a scheme should have practical results, and he appealed to the engineers in the telephone field to try the experiment for verification.[12] Sir William H. Preece, who was at the head of the British telegraph and telephone system, was of the opinion that telephone circuits required more electrostatic capacity for transmission over greater distances and had suggested that the wires be split with insulation between, to increase the capacity by their close juxta-position. Thus the ideas of Heaviside fell on deaf ears in his own country. This is very finely expressed in the graceful tribute which Prof. M. I. Pupin paid Heaviside in his remarkable paper before the American Institute of Electrical Engineers describing the first Heaviside loaded line which he devised in his laboratory at Columbia University and described in his paper in May, 1900. The test for which Heaviside had waited seven years had at last been made in the most successful manner, and it had confirmed for all time the accuracy and the skilful analysis of the theory of the propagation of electromagnetic induction. In a sense Prof. Pupin's confirmation of Heaviside's theory was not unlike the finding,

[11] See a paper by Thomas Shaw and William Fondiller, Development and Application of Loading for Telephone Circuits", *Trans. A.I.E.E.*, 1926, p. 268.

*Continued from the JOURNAL for Jan. 1928, p. 31.

[12] " . . . they will want to know whether such possibilities can be converted into actualities, and whether the conversion is practicable. For myself, I am not much concerned in this part of the question. It is for practicians to find out practical ways of doing things that theory proves to be possible, or not to find them if they should be impracticable." Electromagnetic Theory, Vol. I, p. 441.

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on the part of Prof. Galle, of the outermost planet Neptune in exact position of the heaven where the calculations of the brilliant Leverrier and of Adams had placed it, without ever having known of its existence. But we must let Prof. Pupin voice his own sentiments by giving here a quotation from his paper.[13] "Mr. Oliver Heaviside of England, to whose profound researches most of the existing mathematical theory of electrical wave propagation is due, was the originator and most ardent advocate of wave conductors of high inductance. His counsel did not prevail as much as it deserved, certainly not in his own country."

Pupin's experimental cable was a very beautiful piece of work. It followed the example of Varley and Muirhead in making an artificial laboratory cable or line on which measurements could readily be made which were otherwise difficult to make, as on an Atlantic cable. Thus in the widest sense a confirmation of the theories of Heaviside could be carried on, advancing greatly the art of long distance telephony.

As Prof. Pupin pointed out, little recognition had come to Heaviside in his own country. But there was recognition in France at the hands of the chief of the postal system of the fundamental principles laid down by Heaviside. As it is of great historical interest we here quote from a paper by M. Devaux-Charbonnel, chief engineer of the posts and telegraphs of France.[14] On p. 167 the French chief of the postal service remarks that, as early as 1887, Vaschy, then the engineer of the postal service, solved the partial differential equation of electromagnetic propagation and did this independently of Heaviside, whose papers in the *Philosophical Magazine* reached him, however, before the appearance of his own paper, so that he could give Heaviside full credit for his priority. M. Devaux-Charbonnier further states (on p. 165), that the French Postal Administration undertook to make loaded cables of the type of Krarup and Pupin in 1896 and 1897, which in no essential way differed from these cables. Such work was undertaken by M. Barbarat of the French Postal Service. Thus we may add the tribute of official France to our own in rendering recognition to the distinguished British scientist.

### THE DISTRIBUTION OF INDUCTANCE IN LUMPS ALONG THE CABLE

The question as to the distance at which such inductance coils for loading the line should be placed has been one of the fascinating aspects of the entire problem. Heaviside suggested in 1893 that they be placed about one per kilometer so that there should be a sufficient number spread over the shortest wave length to be transmitted. Pupin, in the paper cited, figures the shortest wave length as about 14 miles or 22 kilometers so that, if Heaviside's suggestion were followed, there would be about 22 coils per wave length. The problem of simulating a uniformly loaded cord by loads placed a certain distance apart and determining the period of vibration of the configuration was proposed first by Lagrange.[15] It is one of the regular exercises in French treatises on dynamics. But it had not yet been applied to the electrical case, and thus Pupin filled in this gap. He found, as was to be expected from the identity of the mechanical and electrical cases, that Lagrange's relation, to wit, the frequencies of vibration varied as sin $\alpha/2$ to $\alpha/2$ holds also for the electrical case. This relation thus yields readily a comparison between a loaded cable and a uniform cable. In practice the loads are close together and the criterion is invariably fulfilled automatically. A most useful formula for this condition has also been given by G. A. Campbell.[16] This formula proved identical with one obtained for a loaded string by Charles Godfrey.[17] Prof. Kennelly has obtained these formulas in a very simple manner in Appendix G of his book "The Application of Hyperbolic Functions to Electrical Engineering Problems" under the heading "A Brief Method of Deriving Campbell's Formula." These references have been carefully compiled on account of the difficulty in locating the important papers. It is hoped that these references will prove useful as the study of the papers cited here appears essential to an understanding of the mechanism of the transmission of speech or power over long lines. These papers also crown as a sort of superstructure the work of Heaviside with which we are here primarily concerned.

The groundwork of science grows in a very slow procession. While a great flood of ideas and papers pours forth from the fertile human mind, there are only a few which can be, and should be, made into the groundwork of science. The comprehension of fundamental principles is of the utmost value, not only to the sound progress of science, but also to the value of science as a means for the cultivation of the mind. It is, on this account, that an outline of the theory of electric propagation is given here which can be applied to the solution and understanding of new problems. Heaviside's contributions have been fundamental, and his mode of attack is growing in favor so that, in a few years' time, our textbook will present his doctrines, whether under his name or not, to the students of electricity.

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[13] Trans. A.I.E.E., p. 450, Vol. XVII, 1900.

[14] "La Contribution des Ingénieurs Francais à la téléphonie à grande distance par cables souterrains. Vaschy et Barbarat." Par M. Devaux-Charbonnel, Ingénieur en Chef des Postes et Télégraphes. *Annales des Postes, Télégraphes et Téléphones,* VI Année, No. 2, 1917. Paris, A. Dumas, Editeur.

[15] J. L. Lagrange, *Mécanique Analytique,* 3rd edition, by M. J. Bertrand. Vol. I, Sect. VI, Par. III, 50, p. 353. Paris, 1853. Henri Bouasse, *Cours de Mecanique Physique,* Par. 495, p. 597, 1912.

[16] In a paper "On Loaded Lines in Telephone Transmissions", *Phil. Mag.,* Series VI, Vol. V, p. 313, March 1903.

[17] *Phil. Mag.* XVI, p. 356, 1898. Mr. Campbell states: "An interesting contribution to the general properties of this structure has been made by Mr. Charles Godfrey in a paper on wave propagation along a periodically loaded string and I am indebted to that article for equation (18) which furnishes a complete solution of the propagation."

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MAXWELL THEORY; THE RELATIONS BETWEEN MAGNETIC FORCE AND ELECTRIC CURRENT

The death of James Clerk Maxwell in 1879 had left his magnificent work completed, though in a form which offered formidable analytical difficulties even to such masters as Kelvin, Fitzgerald, Lodge, and Hertz. These were his principal exponents. The difficulty lay, first, in Maxwell's formulation of the two fundamental equations of the electromagnetic field, secondly, in the application of these fundamental equations to the solution of both simple and recondite phenomena.

There is a distinct parallel between the work of Maxwell and the formulation, by Sir Isaac Newton, of the three Laws of Motion which bear his name. As the whole structure of the science of the motion of particles and rigid bodies is based upon, and clarified by, Newton's three laws, so the science of electromagnetism is based upon the two circuital laws first formulated by Maxwell, and thrown into a simple and manageable form by Oliver Heaviside. This achievement required a degree of abstraction, both mathematical and philosophical, in which Heaviside's great mind was aided by the seclusion and solitude in which he spent his life.

As few of our readers are familiar with the conception of a vector and its "curl" and with the "circuital" equations, Heaviside's elementary exposition of these relations is certain to be welcomed. First, a word about the terminology. The reader frequently comes across the words curl and circuitation in connection with theoretical work in electricity. Maxwell coined the word curl to express the line integral around a closed curve connecting this line integral with the surface integral of another directed quantity or vector through the curve. The theorem involved is that known as Stokes's theorem which is fundamental in the derivation of the electromagnetic equations. Lord Kelvin coined the word circuital[18] to indicate the annular "portion of the ether uniformly all round its circuit". Thus the circular lines of force or induction around a long electric circuit are said to be "circuital all round the circuit". Heaviside gives a really simple method of obtaining the curl of the vector, either of the magnetic force **H** or of the electric force **E**. It may be as well to remind the reader that what we call magnetomotive force is the line integral, or the curl, of the magnetic force **H**; and what we call electromotive force is the line integral or the curl of the electric force.

We must refer the reader to Heaviside's "Electrical Papers", vol. I, p. 195 which contains perhaps one of the clearest expositions found throughout his writings. Textbook writers would do well to quote this chapter word for word to render the theory in Heaviside's words instead of in their own, as is frequently the practice of writers on dynamics who quote Newton verbatim instead of improving on his wording by using their own. While I must refrain from quoting Heaviside in full, I will give here his introductory remarks on account of their general interest. "Everyone knows that electric currents give rise to magnetic force and has a general notion of the nature of distribution of the force in certain practical cases, as within a galvanometer coil, for example. Further than this, few go. The subject is eminently a mathematical one, and few are mathematicians. There are, however, certain higher conceptions, created mainly by the labors of eminent mathematical scientists, from Ampere down to Maxwell, which are usually supposed to be within the reach of none but mathematicians, but which I have thought could be to a great extent stripped of their usual symbolical dress, and in their naked simplicity, made to appeal to the sympathies of the many. Let not, however, the reader (if he belong to the many) imagine that thinking can be dispensed with; there is no royal road to knowledge, and hard thinking and rigid fixation of ideas are required. Even the machinery of the mathematician, so great an assistance when made to work, requires severe training on the part of the operator to make it work. But earnest students, if they will not or cannot learn the mathematical methods, need not therefore be discouraged, for the name of Faraday will shine forth to the end of time as a beacon of hope and encouragement to them. He was no mathematician, yet achieved results apparently only attainable by such methods. It need not be supposed that he had the peculiar brains of a calculating boy, able to do long sums "in his head" by special methods of his own. The work was of quite a different kind, and probably Faraday could never have made an ordinary mathematician, with the best of training. In fact, mathematical reasoning does not necessarily involve any calculating in the usual sense, though it is, of course, greatly assisted thereby sometimes; and as for the use of symbols, they are merely a sort of shorthand to assist the memory, which even those who openly condemn mathematical methods are glad to use so far as they can make them out—in the expression of Ohm's law for instance, to avoid spinning a long yarn."

Heaviside then develops the two equations of Maxwell's in the following form:—

*First Cross Connection of Magnetic and Electric Force*:—This is expressed by,—

$$curl\ \mathbf{H} = 4\pi\mathbf{J}$$

where curl **H** is the vector whose rectangular components are,—

$$\frac{dH_3}{dy} - \frac{dH_2}{dz}, \qquad \frac{dH_1}{dz} - \frac{dH_3}{dx}, \qquad \frac{dH_2}{dx} - \frac{dH_1}{dy}$$

But the most useful definition is the following:—"The line-integral of a vector **H** around any closed curve or circuit (or the circuitation of **H**) equals the surface integral of another vector, viz., curl **H**, over any surface bounded by the circuit".

*Second Connection Between Electric Force and Magnetic Force*:—"The total e.m.f. of induction around

[18] See "Mathematical and Physical Papers," vol. III, p. 451.

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a circuit equals the rate of decrease of the amount of magnetic induction through the circuit.

$$curl\ \mathbf{E} = -a\mathbf{B}/dt = -\mu\, d\mathbf{H}/dt$$

"As the rate of increase of the displacement in a non-conducting dielectric is the electric current, so the rate of increase of $\mathbf{B}/4\pi$ may be called the magnetic current. Let it be $\mathbf{G}$. Then,—

$$\mathbf{G} = d\mathbf{B}/dt \cdot 1/4\pi \quad (Magnetic\ Current)$$

Like electric displacement currents, magnetic currents are transient only, i.e., they cannot continue indefinitely in one direction only, like an electric conduction current. Also, like electric currents in a dielectric, they are unaccompanied by heat generation. In ether the electric current and the magnetic current are of equal significance.

"There is probably no such thing as a magnetic conduction current, $g\mathbf{H}$ with dissipation of energy. If there be such, analogous to an electric conduction current, then let,—

$$\mathbf{J} = k\mathbf{E} + c/4\pi \cdot d\mathbf{E}/dt \quad (True\ Electric\ Current)$$
$$\mathbf{G} = g\mathbf{H} + \mu/4\pi \cdot d\mathbf{H}/dt \quad (True\ Magnetic\ Current)$$
$$-curl\ \mathbf{E} = 4\pi\mathbf{G}$$
$$curl\ \mathbf{H} = 4\pi\mathbf{J}$$

where $k$ is the conductance and $c$ is Maxwell's specific inductive capacity of the dielectric or medium.

In this symmetrical form the equations of the electromagnetic field have been written by Heaviside and this is the form in which they are used today by the foremost physicists of the world. I have not given the full derivation as presented by Heaviside, but I have sketched in rough outline his method and the final form of the fundamental equations. The conception of a magnetic current corresponding with the current in a dielectric is clear and useful from a physical standpoint.

### MATHEMATICAL METHODS

Heaviside developed two branches of mathematics which are of great value. The first is the method of vector algebra, and the second is the use of "operators" and of divergent series for the solution of unmanageable differential equations.

Wherever directed quantities are encountered it is common sense to avoid the writing down of lengthy trigonometric equations which become so jumbled that no one knows what to do with them. Vector addition and subtraction are now in general use, but vector multiplication and division as well as extracting roots are really of an elementary character. And yet how few of the readers of this paper are familiar with vector multiplication! To multiply two vectors or complex quantities $A\ \underline{/\alpha}$ and $B\ \underline{/\beta}$ means multiplying $A$ and $B$ and adding $\underline{/\alpha}$ and $\underline{/\beta}$. Heaviside's proof was, "it works." He insisted that mathematics was an experimental science and that our vector product above was a sort of short-hand which seemed to work wherever applied. Thus $A\ \underline{/\alpha} \times B\ \underline{/\beta} = AB\ (\underline{/\alpha} + \underline{/\beta})$. But other definitions can be given to a vector product. The one at present commonly adopted defines a vector product as a vector at right angles to the original vector planes and of a certain magnitude, as this is useful in electromagnetic theory and in dynamics. There was nothing new in these methods in Heaviside's time except that they fitted the problems to be worked. Every active electrical engineer today uses the complex quantities which Steinmetz and Kennelly have made so familiar. One could not get along without them, and for this Heaviside deserves as much credit as the two able men named.

It was Prof. Eddington, himself a famous mathematician, who remarked that a mathematician was never so happy as when he wrote on something he did not understand, and Heaviside likewise talks of mathematicians "inventing difficulties". He also remarks[18] "An eminent authority once remarked that there is a lot of humbug in mathematical papers. He knew, having done it himself several times." Now, something like this we frequently encounter in modern mathematical applications. Heaviside's interpreters would hardly have been pleased with his own comments on their labors. He disliked the theory of functions, he thought most mathematics dull, with the exception of Fourier. He thought most rigorous proofs silly. (E. M. T. III, 140). "It seems to me that the demonstration I have poked fun at is typical of a lot of work made up by the brain-torturers who write books for young people and college students who are going to be senior wranglers, perhaps. Let mathematicians be humanized if possible. The best of all proofs is to set out the fact descriptively, so that it can be seen to be a fact."

The simplest examples of operators are the complex numbers. We say that the operator $j$ turns a directed quantity from the abscissa or $x$-axis counter-clockwise or positively into the $y$-axis so that $jx = y$. If you wish to turn it through another quarter phase multiply it again by $j$ and you have $jjx = j^2 x = -x$. The definition of $j$ is given by $j^2 = -1$ and not by $\sqrt{-1} = j$. Why make a mystery of this? It is short-hand, nothing more or less. But why stop here? Brilliant mathematicians, like the late William Kingdon Clifford, had a way of demonstrating these irrational or complex operations which it may be worth while to repeat for the benefit of people who like to know what all this talk about operators really is about. We will begin with Lord Kelvin's famous "compound interest law." If the differential coefficient of a quantity is proportional to the quantity itself, Lord Kelvin would put it that "they follow the compound interest law." Let $y = Ae^{ax}$, then $\frac{dy}{dx} = aAe^{ax} = ay$. Thus, if we know that a function grows in such a manner that its rate of increase or decrease is proportional to the function itself, then we know that the function is a logarithmic function of the order of $y$ given above.

Clifford went a step farther. If a quantity grows at logarithmic rate $jx$, he argued, it means what? Write

[18] *E.M.T.* III, p. 51.

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down $\epsilon^{jx}$ and interpret it, but how? Algebraically it is equal to,—

$$\epsilon^{jx} = 1 + jx + \frac{(jx)}{1\cdot2} + \frac{(jx)^3}{1\cdot2\cdot3} + \frac{(jx)^4}{1\cdot2\cdot3\cdot4} + \ldots\ldots$$
$$= 1 + jx - \frac{x^2}{2} - j\frac{x^3}{6} + \frac{x^4}{24} -$$

Represent this graphically as in Fig. 2. It shows that, assuming $x = 1$, the operator $\epsilon^{jx} = \epsilon^{j}$ has turned the step 1 of the above equation counter-clockwise through $x = 1$ radians. Give to $x$ different values and the operator keeps on turning the step round and round and round. Hence, it follows that, as the radius vector $OP$ is equal to $cos\ x + jsin\ x$, and as $OP$ in magnitude and position is equal to $\epsilon^{jx}$, there follows Euler's important formula,—

$$\epsilon^{jx} = cos\ x + j\ sin\ x$$

From the same figure follows,—

$$\epsilon^{-jx} = cos\ x - j\ sin\ x$$

Hence,—

$$2\ cos\ x = \epsilon^{jx} + \epsilon^{-jx}$$

or,—

$$cos\ x = 1/2\ (\epsilon^{-jx} + \epsilon^{jx})$$

If the several terms of the series for $cos\ x$ be now worked out and constructed step by step, we again ob-

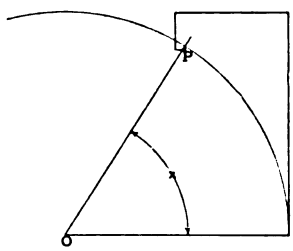

FIG. 2—A GRAPHICAL REPRESENTATION OF COS X

tain a graphical representation of $cos\ x$. It is done in Fig. 2 for $x = 1$, from

$$cos\ x = 1 - \frac{1}{2}x^2 + \frac{x^4}{1\cdot2\cdot3\cdot4} - \frac{x^6}{1\cdot2\cdot3\cdot4\cdot5\cdot6} + \ldots\ldots$$

These terms are now all real and are laid off on the abscissa. While these graphical representations may appear too elementary, it is due to the disregard of elementary methods that mathematical analysis has grown to be viewed skeptically.

These algebraical expressions are totally meaningless without their geometrical interpretation. The moment hard common sense is injected into mathematical argument, it usually appears that a new light and understanding are brought to bear on the task. As algebra is now taught in school one may be pardoned for agreeing with Heaviside that it is "barbarous" and "inhuman", but it certainly is nothing of the kind in the hands of a John Perry or a William Kingdon Clifford.

The two most important contributions to engineering mathematics made by Heaviside are his chapters "On Resistance and Conductance Operators and their Derivatives", published on pp. 355 and 371 of "Electrical Papers", Vol. II, and "The Expansion Theorem. Operational Way of Getting Expansions in Normal Functions", to be found on p. 126, of "Electromagnetic Theory", Vol. II.

The last ten years have seen a great wave of appreciation of these papers now thirty years old. A school has been brought into existence with its center in the Massachusetts Institute of Technology where, under the leadership of Prof. V. Bush, a number of postgraduate theses have been based successfully on Heaviside's "expansion theorem." At the Franklin Institute there have been presented recently papers by E. J. Berg, J. J. Smith, Louis Cohen, etc., all of which having for their aim the application of Heaviside's methods to the solution of certain problems in electrical engineering which had heretofore resisted the conventional methods. The American Institute of Electrical Engineers has witnessed a long list of papers by Professors Bush and Vallarta, by Prof. Lyon and Dr. Carson and others applying Heaviside's methods to their problems.

The solution of the distribution of e.m.f. and current in alternating-current circuits in the steady state has been made possible for all known configurations by the use of resistance and conductance operators. Solutions of the transient state have been given by Heaviside, using his expansion theorem, for the sudden application of a constant potential to a circuit. The sudden application of a sinusoidal potential has been worked out also in some of the papers referred to. The difficult answers are even more difficult to interpret in the majority of cases which are at all amenable to a solution. Progress in this direction is perhaps now more needed in extending the "algebrization"—a term frequently used by Heaviside—of the operational solutions. But in many cases it is very difficult to represent the algebraical solution so that it has any meaning in a physical sense. This is a large field in which much work has to be done.

### WORK IN OTHER FIELDS

It is not to be wondered at that a genius of the broad interests of Heaviside's type would not have limited himself to the working out of the distortionless circuit and its mathematics, though it would seem a large field indeed in view of what has been built upon this foundation. But Heaviside was interested in mathematical physics and, with his matchless skill in the application of mathematics to this subject, he engaged in numerous critical ventures which may have created the totally wrong idea that he was given to disputation. It is interesting to note that he thus had occasion to point out serious errors made by Lord Kelvin. He pointed out errors in Prof. Peter Guthrie Tait's treatise on quaternions. He analyzed a paper by Sir Joseph J. Thomson, then Professor J. J. Thomson, "On Electrical Oscillations in Cylindrical Conductors" and was forced to conclude that "the use of an erroneous boundary condition in the beginning wholly vitiates the subsequent results." (E. P., II, p. 396). His numerous encounters with Sir William Preece, the head of the posts and telegraphs of Great Britain, in which, of course, the late Sir William was invariably wrong, added

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to the impression that Heaviside was a most formidable opponent in the arena of science. He was always most kind and considerate except in the case of Preece whom he held up to scorn for his lack of understanding combined with great assurance which goes so often with official ignorance. This was in a sense unfortunate, at least for Heaviside personally, though it doubtless helped to correct the errors of these most eminent men.

In the application of Fourier's theory to a great cosmical example Lord Kelvin saw an opportunity to calculate the age of the earth from her secular cooling. There were some data available, to be sure very meager, which made it possible to calculate the heat gradient, and from it the time when the center of the earth must have been so hot that all known elements would exist only in a gaseous state. The application of Fourier was beautiful, but the result was disastrous, at least to the geologists and the great school of the followers of Darwin and Huxley and the theory of evolution. Lord Kelvin was led to believe that the limiting age of the earth was less than fifty million years and more than ten million years. Prof. Huxley protested, somewhat meekly to be sure, stating that there might be unknown substances in the earth which might lead to a different result. This, of course, has been the conclusion arrived at after the discovery of radio-active substances, but Huxley did not prevail against the most illustrious representative of British science. Then, in 1895, Prof. Perry, a close friend of both Heaviside's and Lord Kelvin's whose assistant he had been, proposed to Heaviside solving the Fourier equation for rocks with different conductivities in series, so to speak. Conventional mathematics could not solve this problem but Heaviside succeeded in solving it and in proving that the age of the earth could thus be easily a thousand times greater than Lord Kelvin's estimate. Sir Ernest Rutherford and his school have since added any number of years that might be required by geologists or biolgists to meet their theories. Both the Kelvin theory and the Heaviside-Perry enlargement thereof are now useful applications of mathematics to physical problems.

It is interesting to allude to another example where Lord Kelvin and Tait made an error in their monumental work on "Natural Philosophy". This was pointed out by Heaviside in "Electrical Papers", II, p. 245, and refers to the treatment by the illustrious authors of the St. Venant problem of torsion. Such corrections, if viewed impersonally, become of the utmost interest and value to the cause of science, as they show the fallibility of the greatest of our leaders and the necessity for free discussion untrammelled by the ignorance and narrow-mindedness of those whom we may call with Herbert Spencer the "must-be-rights". The errors of Newton and Lagrange, to mention just two great names, have done much harm until resolute criticism brought them to the bar. Thus let it always be! No man living or dead should be exempt from criticism so long as such criticism is based on fact and fairness.

Heaviside became greatly interested in the discovery, in 1897, of the "corpuscle" by Sir J. J. Thomson. This is now called the electron after the example by Johnstone Stoney. It appeared to him that the mass of a moving particle, when the velocity approached that of light, would be a function of this velocity. He developed the equations which are now fundamental.

In the words of Sir Oliver Lodge, Heaviside left his name on the atmosphere, as it was he who first called attention to the existence of an ionized layer in the atmosphere which acted as a reflecting medium for the Hertzian waves. In his own words, "Sea water, though transparent to light, has quite enough conductivity to make it behave as a conductor for Hertzian waves, and the same is true in a more imperfect manner of the earth. Hence the waves accommodate themselves to the surface of the sea in the same way as waves follow wires. The irregularities make confusion, no doubt, but the main waves are pulled round by the curvature of the earth, and do not jump off. There is another consideration. There may possibly be a sufficiently conducting layer in the upper air. If so, the waves will, so to speak, catch on to it more or less. Then the guidance will be the sea on one side and the upper layer on the other." ("El. Mag. Theory", Vol. III, p. 335, June 1902).

THE END

This narrative makes no attempt at rendering a complete picture of the work during a very long life of one of England's most powerful interpreters of physical phenomena. But it would be even more woefully incomplete if, as a fitting postscript, it were to omit a recital of many of the happy and humorous thoughts and ideas which brighten the 2700 pages, in fine print, and rife with mathematical formulas. Readers would have ground for not forgiving me if I were to withhold from them gleanings so interesting and so picturesque and clear that even those who care nothing for mathematical treatment of physical phenomena would enjoy these five volumes. James Swinburne, reviewing in "Nature" for December 20, 1894, the first volume of the "electromagnetic theory" says toward the close: "The style is that of Whitman, except that Mr. Heaviside is not affected, and has something to say. The similarity is also noted in the *Philosophical Magazine*. Every line of the book is important, and it is full of interesting digressions on all sorts of subjects. Though the converse may not be true, all clever men have a sense of humor, and it is therefore a pity that scientific writers emulate the ponderous dryness of the theologian. Mr. Heaviside's work bristles with humor of a type which he has invented."

As readers might like to check quotations from Heaviside's works, I shall designate the "Electrical Papers" by *E. P.* and the "Electromagnetic Theory" by *E. M. T.* and our first quotation shall be, "Storage Room

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is Too Valuable." (*E. M. T.* II, p. 433.) "For the benefit of the uninitiated, I should explain that El. Pa. means my "Electrical Papers". They can be picked up cheap, because the remainder was sold off in quires for a few pence per volume, on account of the deficiency in storage room. Though somewhat vexed at first by this disposal of my labored lucubrations, it has later, given me and others occasion for much laughter." (*E. M. T.* III, p. 93.) "Note (Nov. 30, 1887). The author much regrets to be unable to continue these articles in fulfilment of Section XI, having been requested to discontinue them." (*E. P.* II, p. 155.)

Now these are the papers which have since been unobtainable. They have sold at $75 for the two volumes and they made desirable a photographic reprint which is now available. It is certainly a bit of humor that the inventor of long distance telephony, while he was explaining his invention, was asked by his publishers to stop. Fortunately for the telephone the gag was removed after a little time.

Under perpetual irritation from the leading mathematicians of Cambridge, who did not read his work but condemned it, he wrote, "Whether good mathematicians, when they die, go to Cambridge, I do not know." (*E. M. T.* III, p. 175.) In discussing Lagrange's equations and the principle of least action, he says, "Truly, I have never practiced it myself (except with pots and pans)....." (*E. M. T.* III, p. 175.) "If it is love that makes the world go round, it is self-induction that makes electromagnetic waves go round the world." (*E. M. T.* III, p. 194.) In regard to Lagrange's equations he says, "Is not Newton's dynamics good enough? Or do not the Least Actionists know that Newton's dynamics, viz., his admirable Force = Counterforce and the connected Activity principle, can be directly applied to construct the equations of motion in such cases as above referred to, without any of the hocus-pocus of departing from the real motion, or the time integration, or integration over all space, and with avoidance of much of the complicated work? It is against the misuse that I write." (*E. M. T.* III, p. 176.) "When I was a young child I conceived the idea of infinite series of universes, the solar system being an atom in a larger universe on the one hand, and the mundane atom a universe to a smaller atom, and so on." (E. M. T. III, p. 172.) "....Faraday,....that great genius had all sorts of original notions wrong as well as right and, not being a mathematician, could not effectually discriminate...." (*E. M. T.* I, p. 415.) "Some do not believe in the materiality of the ether. This view is throughly anti-Newtonian, anti-Faradaic and anti-Maxwellian. What mean action and reaction, the storage of energy, the transit of force and energy through space, etc., if there is no medium in space? For space is nothing at all, save extension. Lord Kelvin used to call me a nihilist. That was a great mistake. (though I did throw a bomb occasionally, to stimulate an official humbug to learn something about electricity and how to apply it)....I have observed repeatedly that young to-be physicists, when they leave college, are full of generalized co-ordinates, and the theory of functions, and unnatural spaces, and rigor; but when they become thoroughly immersed in real physics, even though mathematical, a lot of the learning referred to fades away. Is Cambridge to blame? Perhaps not. It may be my fault." (*E. M. T.* III, p. 479.)

The war came and with it much hardship and suffering for the aged scholar. Let us keep the gaze of the world from the last years of the master. At last the great light went out. *Sic percat gloria mundi!*

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# Fractional Pitch Winding for Induction Motors

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TO to the student of electrical machinery, the windings and coil connections of rotating machines are both interesting and difficult to understand. This is particularly true of the induction motor, in which the primary windings carry both the load and the magnetizing currents, and in which any change in the coils or connections alters all of the motor characteristics.

Windings having two coil-sides per slot and fractional-pitch or "chorded" coils are universally used on the larger motors in this country. The fractional pitch winding is used for one or more of the following reasons:—

1—To obtain the effect of a number of turns per coil intermediate between that secured by the addition or removal of a turn.

2—To save copper in the end connections, decreasing phase resistance.

3—To shorten the coil extension from the core, resulting in a shorter machine with stronger coil-ends.

4—For machines having few poles, to permit placing the coils in the slots without excessive bending.

5—For two-speed motors, to permit the use of the "consequent-pole" connection.

6—To secure certain locked secondary voltages for a wound rotor, where there is a limitation in this respect.

7—To reduce space harmonics in the field form.

## FLUX-VOLTAGE RELATIONS

A good motor should have a certain balance between performance, distribution of losses, and economy of materials. In the induction motor, such balance is obtained by correct choice of air-gap induction, i.e., by using the proper number of turns per coil in the primary winding. For full-pitch coils,—

$$\phi = \frac{\text{Phase voltage} \times 10^8}{2.22\ ZfD}$$

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Where
$\phi$ = flux per pole
$Z$ = series conductors per phase
$f$ = frequency of supply
$D$ = distribution factor
= 0.955 three-phase
= 0.905 two-phase

The many combinations of motor speeds, voltages, and frequencies for which the primary coils must be designed require considerable flexibility in the number of series turns per phase. To secure good motor performance, the smallest induction motors use partially-closed primary slots in which are placed many turns of small wire. With so many turns, the required variations in air-gap induction may be met in the majority of cases by adding or subtracting turns.

For the larger motors, which in this country invariably use open primary slots, completely-formed diamond coils, and two coil-sides per slot, this is not always possible. Such motors have a sufficiently high induction per pole that comparatively few turns are required. In the interests of space economy, rectangular-section conductors and few turns are used, consistent with mechanical considerations and the necessity for minimizing eddy-currents. To obtain the effect of having a number of turns intermediate between that obtained by adding or removing a physical turn, the coils are chorded or made of fractional pole-pitch. The result is that the induced voltages in the two coil-sides do not reach their maxima at the same time, i.e., the two voltages $E_a$ and $E_b$, Fig. 1, are thrown out of phase with each other by an angle $\beta$. For a given line voltage, there results an increased flux per pole with decreased coil pitch.

Thus the winding effectiveness may be reduced, and the designer may thereby obtain the desired flux per pole more nearly than would be possible by changing the number of turns.

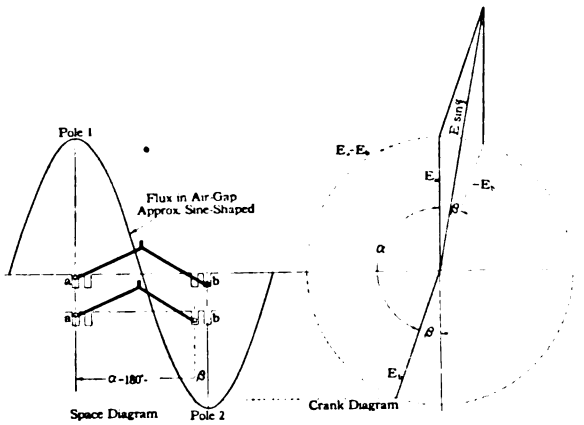


FIG. 1—THE EFFECT OF CHORDING AN INDUCTION MOTOR WINDING ON THE COIL VOLTAGE

The ratio between the effectiveness of the winding at fractional and full pitches is called the chord factor, and is numerically equal to the sine of half the electrical angle spanned by the coil. For full pitch, the angle is 180 degrees, and the chord factor = 1.00. Chording is carried down to 50 percent pitch, in certain cases.

Referring to Fig. 1, if $E/2$ is the voltage generated by either coil-side, the coil voltage for full pitch = $E$, and for any other pitch,—

$$E_c = 2\left[\frac{E}{2}\cos\left(\frac{\beta}{2}\right)\right] = E\cos\left(\frac{\beta}{2}\right) = E\sin\frac{\alpha}{2}$$

The chord factor $C = \sin\frac{\alpha}{2}$, and is shown in Fig. 2 plotted against percent coil pitch. The curve shows the possibilities of changing the flux per pole

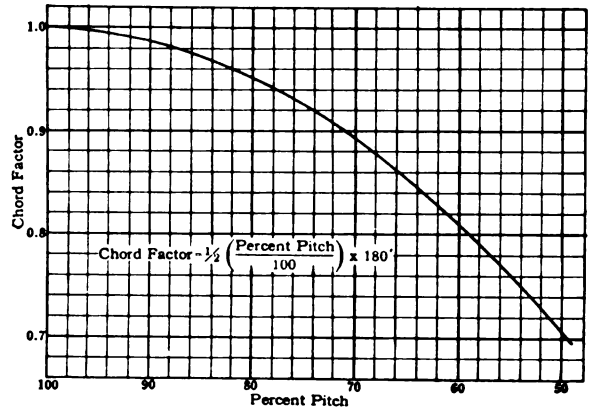


FIG. 2—THE VARIATION OF CHORD FACTOR WITH PITCH

without changing the number of turns in the primary coil. Note that a considerable reduction below full pitch is permissible before the chord factor is seriously reduced.

The flux-voltage equation for fractional-pitch coils now becomes,—

$$\phi = \frac{\text{Phase voltage} \times 10^8}{2.22\, ZfD \times C}$$

As an example, consider a three-phase, 10-pole primary winding, connected parallel star for a 60-cycle, 2200-volt circuit. With 9 slots per pole, and 5 turns per coil, the series conductors per phase $Z$ = 150, and $\phi$ = 6 650 000 lines. This is for a full-pitch winding (C = 1.00).

However, should the designer require about six percent more induction than this, he must resort to

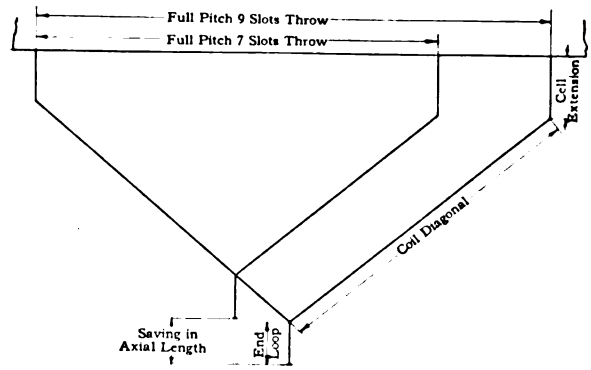


FIG. 3—CHORDING A WINDING (UP TO A CERTAIN EXTENT) RESULTS IN A SAVING OF COIL LENGTH

chording. Removing a turn from the coils would increase the induction too much. With a throw of 1-8, (77.8 percent of full pitch), C = 0.94, and $\phi$ = 7 080-000 as required.

### EFFECT ON COIL EXTENSION

The use of a fractional-pitch winding reduces the length of the end-turn connecting the coil sides, and

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shortens the coil extension from the core. In Fig. 3, the length of the coil diagonal is decreased with a shortened coil pitch, whereas the part of the coil embedded in the core, the cell extensions, and the end-loop remain unchanged. Not only is the total resistance per phase decreased, but the shorter coil extension may often permit the use of a narrower frame casting and a smaller shaft than would be possible with full-pitch coils. This is particularly true of motors having a small number of poles.

For machines of small core-width and large pole-pitch, the reduction in resistance by the use of fractional-pitch windings is appreciable. However, for large motors having a small pole-pitch, the change is not great.

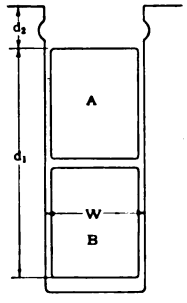


FIG. 4—AN INDUCTION MOTOR SLOT

### EFFECT ON THE MAGNETIZING CURRENT

The effectiveness of the primary winding to generate a counter e.m.f. with a certain air-gap induction decreases with the amount of chording, and in the same manner, the effectiveness of the winding m.m.f. to create a definite air-gap flux decreases with shortened coil throw. For a fixed line voltage, the air-gap induction varies inversely as the chord factor, so that the portion of the magnetizing current required to excite the air-gap will increase inversely as the square of the reduction in the chord factor. Increased air-gap inductions mean additional ampere-turns used in the magnetic circuit, as these parts become more nearly saturated, so that, in general, the total magnetizing current increases somewhat more than the square of the chord factor.

### EFFECT ON REACTANCE

To appreciate fully the effects of chording, one must consider not only the reduced coil resistance, but also the change in reactance. In general, coil pitches

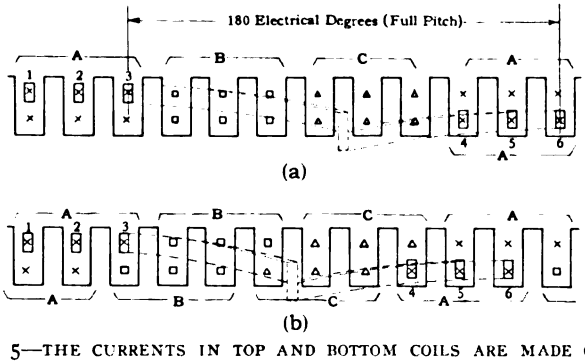


FIG. 5—THE CURRENTS IN TOP AND BOTTOM COILS ARE MADE OUT OF PHASE BY CHORDING

between 80 and 90 percent of full pitch are most desirable for the average induction motor. Above 90 percent, an unnecessary amount of copper will be placed in the end connections, while below 80 percent pitch, the reactance is not reduced in proportion to the chord factor, with poorer overall motor characteristics.

This is but a general rule, since the limitations to chording, together with choice of iron and copper densities, represent one of the requirements of a balanced design which differ for the various sizes and speeds of motor.

*Slot Reactance*—Consider first the reactance of the embedded conductors. A general expression for the slot reactance per phase, with full-pitch coils in open slots, may be found in several text-books* on induction motors:—

$$X_s = \frac{2\pi f P Z^2 l'}{S \times 10^8} \times \phi_s$$

Where $\phi_s$ = leakage flux per ampere-conductor per inch length of slot.

$$= 3.2\left(\frac{d_1}{3W} + \frac{d_2}{W}\right) = 3.2\,K_s$$

$K_s$ is called the "slot factor"
$P$ = No of phases
$Z$ = Series conductors per phase.
$l'$ = Net length of core, corrected for flux fringing.
$S$ = Total number of slots.
$d_1$, $d_2$, $W$, See Fig. 4.

This expression is for full-pitch coils, that is, the currents in top and bottom of each slot are in phase. If $\theta$ represents the angle between the two currents, cos $\theta = 1.0$. Referring to Fig. 5(a), note that for a three-phase winding of nine slots per pole, there are three series coils per phase-group; the total slot reactance per phase is the average reactance of the three times the number of groups per phase.

The phase difference between the currents in adjacent phase-groups is sixty electrical degrees. Changing the coil throw from 9 to 8 slots, Fig. 5 (b), places coil-sides 3 and 4 in slots containing coil-sides from the adjacent groups, i.e., the currents are 60 degrees out of phase between the upper and lower coil-sides in one-third of the coils in each phase. The resultant m.m.f. per slot tending to produce leakage flux is reduced from 100 percent, to $100\left(\frac{1+\cos\theta}{2}\right) = 100\left(\frac{1.5}{2}\right)$ = 75 percent for one-third of the coils, or an average

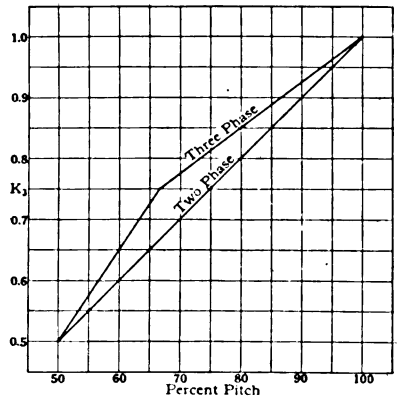


FIG. 6—THE RELATION MAGNITUDE OF LEAKAGE REACTANCE FOR ALL LEAKAGE FLUX ABOVE THE COILS

reduction to 91.7 percent of full-pitch reactance for the complete phase-group.

The chording may be carried further, until at two-thirds pitch the reactance chord factor = 75 percent.

*See Gray's "Electrical Machine Design", p. 220.

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Below this pitch certain slots contain currents 120 degrees out of phase, for which $\cos \theta = -0.50$. The decrease in reactance below two-thirds pitch is accelerated by the introduction of these 120 degree components, as shown in the curves of Fig. 6.

Two-phase windings may be similarly laid out, with two instead of three phase-groups per pole. In this case, the currents in adjacent phases are in 90 degree phase relation, and there is no break in the reactance factor curve at two-thirds pitch. The two-phase relation is also shown in Fig. 6.

This explanation of the effects of chording upon slot reactance assumes that all the leakage flux produced by the m.m.f. per slot crosses the slot above the conductors. However, the amount of leakage flux passing through the conductors may exceed that crossing above them. The simple assumptions of the preceding paragraphs do not hold, since there is relative leakage flux between the top and bottom conductors. The limiting condition, where all the leakage flux passes through the coils, and none above them, is derived in the appendix and shown in Fig. 7. In the actual machine, a fairly definite percentage of the flux passes through the conductors, depending upon the ratio of $d_1$ to $d_2$. Fig. 7 shows the slot reactance factor for the average open-slot winding.

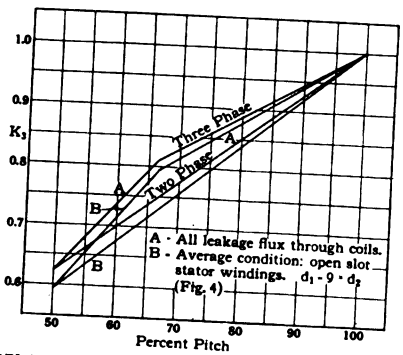


FIG. 7—THE RELATIVE MAGNITUDE OF LEAKAGE REACTANCE WHERE ALL LEAKAGE FLUX PASSES THROUGH THE COILS

*Rotor Slot Reactance*—The rotor slot factor contains an addition due to the partially-closed slot opening. The slot factor for this type of slot is

$$K_s = \frac{d_1}{3W} + \frac{d_2}{W} + \frac{2\,d_3}{W+y} + \frac{d_4}{y}$$

using the dimensions given in Fig. 8, windings in partially-closed slots have a greater percentage of leakage flux passing above the conductors. For this reason, the reactance factor for fractional-pitch windings approaches more nearly the *A* lines of Fig. 7, than those for open slot windings, *B*. Rotor windings are usually made of full pitch, so that the factor for partially-closed slots seldom needs to be used.

*End-Connection Reactance*—Roughly, the length of the end-turn beyond the cell extensions varies as the percent pitch and, assuming a constant leakage flux per inch of conductor, the reactance varies as the length of end-connection. For the reactance of the cell extensions, which is usually added to that of the end-turn, the reduction in reactance with chording will be the same as that for the slot reactance, involving the factor $K_3$, Figs. 6 and 7.

*Tooth-Tip or Zigzag Reactance*—Expressions for the tooth-tip reactance are of the same form as those for the slot reactances. So far as fractional-pitch windings are concerned, this part of the motor reactance is affected in the same manner as that resulting from the portion of the slot flux which crosses above the conductors, i.e., is common to both coil-sides. The reactance chord factor will then be $K_3$, and where one formula is used involving both primary and secondary windings, the reactance factor $K_3$ should be averaged for the two windings.

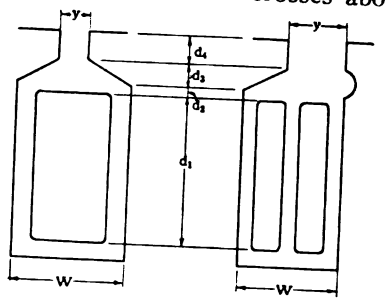


FIG. 8—TYPICAL SLOTS IN A SQUIRREL-CAGE ROTOR (LEFT) AND IN A WOUND ROTOR (RIGHT)

### CONSEQUENT-POLE CONNECTION

For two-speed motors having a speed ratio of two to one, the necessity for using two separate windings may be avoided by the use of a consequent-pole connection. The ordinary three-phase winding has six phase-groups per pair of poles, and is in reality a six-phase winding, with currents in adjacent groups of 60-degree relation. By using a connection which reverses every other phase-group, it is possible to make the phase m.m.f.'s in such a relation that all poles formerly south poles, say, become north poles, the north poles remaining as they were. Since it is not possible to produce north poles without corresponding south poles, the field distributes itself to produce as many south poles as north poles, resulting in an effective number of poles twice that at first, and a reduction in speed to one-half of the former speed.

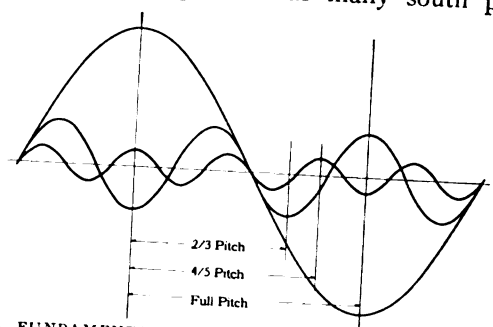


FIG. 9—A FUNDAMENTAL SINE WAVE WITH A THIRD AND FIFTH HARMONIC

If the coils were of full-pitch for the high speed they would be of 200 percent at half-speed, i.e., the winding would not function as a consequent-pole winding. By making the pitch two-thirds for the first condition, this would become 4/3 pitch for the low speed.

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giving the same chord factor for both connections. In actual practise, pitches of ½ at high-speed and full pitch at the low speed are frequently used. Such a design favors the motor performance at the low speed.

### EFFECT OF HARMONICS IN FIELD FORM

The fractional-pitch winding may serve a valuable purpose for certain designs of induction motor in which a full-pitch winding would permit the presence of field-form harmonics. Such harmonics cause trouble in the starting of squirrel-cage motors, where severe dips in the speed-torque curve may prevent the motor from attaining full speed at heavy loads. The motor then runs at some sub-synchronous speed, depending upon the order of the harmonic fluxes causing the reduction in torque. The fundamental, third and fifth harmonics assumed to be present in a certain motor field-form, are shown in Fig. 9. Here a two-thirds pitch coil would bring the third-harmonic voltages in the two coil-sides connected in series into a 180-degree relation, that is, chording to two-thirds pitch prevents the presence of a third-harmonic flux in the air-gap due to the distributed winding. Similarly, chording to four-fifths pitch brings the fifth-harmonic flux voltages in the series coil-sides 180 degrees out of phase with each other, eliminating the fifth-harmonic flux. In general, a harmonic of order $N$ may be eliminated by a reduction in pitch of $\frac{1}{N}$. For intermediate pitches, each harmonic is somewhat effected although not eliminated, so that a pitch half-way between that necessary for the elimination of either of two undesirable harmonics will generally serve the purpose and improve the shape of the speed-torque curve.

The improvement in the shape of the field form improves the electrical balance in the poly-phase circuits, resulting in a minimum of copper losses and reduction in magnetic noises. For the small motors, skewing of the slots through one slot-pitch will usually improve the field form and reduce noise, but for the larger motors, the employment of fractional-pitch windings serves the same purpose.

### APPENDIX

As explained in the text, the curves of Fig. 6 for an open slot assume that all of the coil leakage flux passes above the conductors, and none through them. However, a definite percentage of the flux actually passes through the coils, depending upon the ratio of $d_1$ to $d_2$, Fig. 4. It is interesting to study the effect of fractional-pitch on the reactance of the upper and lower coil-sides, when there is relative leakage flux between them. Self and mutual reactance must be considered, and the average coil-side reactance found by averaging the values for the top and bottom conductors.

First consider a single slot, Fig. 4, with one ampere in each of the two coil-sides. The flux interlinkages in $B$ are—

(1) $\phi_{bb}$ due to its own current.

(2) $\phi_{ab}$ due to current in $A$.

$\phi_b$ = sum of (1) and the in-phase component of (2) = total in-phase flux interlinking $B$ per inch of slot.

With one ampere per coil-side—

$$(1)\quad \phi_{bb} = \frac{3.2}{W}\left(\frac{d_1}{6} + \frac{d_1}{2} + d_2\right)$$

$$(2)\quad \phi_{ab} = \frac{3.2}{W}\left(\frac{d_1}{4} + d_2\right)$$

Since the currents in $A$ and $B$ differ in phase-position by the angle $\theta$, for one ampere distributed uniformly over the slot

$$\phi_b = \frac{\phi_{bb} + \phi_{ab}\cos\theta}{2} = \frac{3.2}{2W}\left[\left(\frac{d_1}{6} + \frac{d_1}{2} + d_2\right) + \cos\theta\left(\frac{d_1}{4} + d_2\right)\right]$$

$$\phi_a = \frac{3.2}{2W}\left[\left(\frac{d_1}{6} + d_2\right) + \cos\theta\left(\frac{d_1}{4} + d_2\right)\right]$$

It might appear that the sine or reactive voltage component induced by the mutual flux leakage had been neglected. However, these components are equal in magnitude for the two series coil-sides of a given coil, and are in 180-degree relation, thus effectively neutralizing each other. Referring to the vector sketch, Fig. 10, a coil in phase 1 has side $a$ in inductive relation to phase 2; the other side $b$ is in the same relation to phase 3, that is $\theta = 60$ for both $a$ and $b$. Since $a$ and $b$ are in series, $E_{13}$ reversed has a sine component which balances the sine component of $E_{12}$. Simply stated, the two reactive voltages induced in phase 1 from phases 2 and 3 will be of equal magnitude and in 180-degree relation to each other.

The effective leakage flux interlinkage per inch length of slot will be the average of $\phi_a$ and $\phi_b$, since each coil has one side in the top of a slot and one in the bottom of another slot; also since $\theta$ will be the same for the slots actually containing the two coil-sides, we may consider the coil, for our purposes, as being entirely contained in one slot, with the number of slots equal to the number of coils. Then.

$$\phi_s = \frac{\phi_a + \phi_b}{2} = \frac{3.2}{W}\left[\left(\frac{5}{24}d_1 + \frac{1}{2}d_2\right) + \cos\theta\left(\frac{1}{8}d_1 + \frac{1}{2}d_2\right)\right]$$

For full pitch, where $\cos\theta = 1.0$, the above becomes:—

$$\phi_s = \frac{3.2}{W}\left(\frac{d_1}{3} + d_2\right) = 3.2\,K_s$$

where $K_s$ = the slot factor as given in the text.

Then for a single slot or coil under consideration, where the currents in the top and bottom conductors differ in phase position by the angle $\theta$, the ratio of the reactance at a fractional-pitch to the reactance at full pitch may be expressed,—

$$K_3 = \frac{\phi_s\ (chorded)}{\phi_s\ (full\ pitch)} = \frac{(5d_1 + 12\,d_2) + \cos\theta\,(3\,d_1 + 12\,d_2)}{8d_1 + 24\,d_2}$$

The angle $\theta$ differs for the various series coils per phase group with short pitch, except at 1/3 or 2/3 pitch for three-phase, and at 1/2 pitch for two-phase. For instance, in Fig. 5*a*, full pitch, for all three series coils in phase-group A, $\theta = 0$ degrees. In Fig. 5*b*, at 8/9 pitch, $\theta$ is zero for two of the coils, and is 60 degrees for the third. Similar reasoning applies to two-phase, except that $\theta = 90$ degrees rather than 60 degrees for slots containing coils for both phases. In general, if $S$ = No. of slots, and $P$ = percent coil pitch, as a decimal, the following table shows the number of coils or slots having various values of $\theta$.

| Extent of Coil Throw | No. of Ph. | Total Slots per Ph. | No. of Slots for Which $\theta = 0$ | $\theta = 60$ | $\theta = 90$ | $\theta = 120$ |
|---|---|---|---|---|---|---|
| 2/3 to full | 3 | $\frac{S}{3}$ | $S\left(P - \frac{2}{3}\right)$ | $S\,(1-P)$ | | |
| 1/3 to 2/3 | 3 | $\frac{S}{3}$ | | $S\left(P - \frac{1}{3}\right)$ | | $S\left(\frac{2}{3} - P\right)$ |
| 1/2 to full | 2 | $\frac{S}{2}$ | $S\left(P - \frac{1}{2}\right)$ | | $S(1-P)$ | |

Since we wish to determine the average coil reactance, it is necessary to express the number of slots for the various values as a decimal percentage of the total number of slots per phase; divide the number of slots for the values of $\theta$ by $\frac{S}{3}$ for three-phase, and by $\frac{S}{2}$ for two-phase.

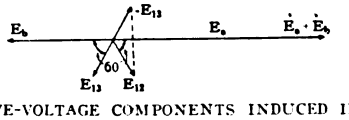


FIG. 10—REACTIVE-VOLTAGE COMPONENTS INDUCED IN PHASE 1 BY PHASES 2 AND 3

| Extent of Coil Throw | No. of Ph. | No. of Slots as a Decimal Percentage of the Total Number of Slots per Phase, Where $\theta = 0$ | $\theta = 60$ | $\theta = 90$ | $\theta = 120$ |
|---|---|---|---|---|---|
| 2/3 to full | 3 | $3\left(P - \frac{2}{3}\right)$ | $3\,(1-P)$ | | |
| 1/3 to 2/3 | 3 | | $3\left(P - \frac{1}{3}\right)$ | | $3\left(\frac{2}{3} - P\right)$ |
| 1/2 to full | 2 | $2\left(P - \frac{1}{2}\right)$ | | $2\,(1-P)$ | |

A general expression for $K_3$ may now be found for the total series coils per phase. Note that for those coils or slots for which $\theta = 0$, $K_3 = 1.00$

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Three-phase, 2/3 to full pitch:

$$K_3 = 3\left(P - \frac{2}{3}\right) + 3(1 - P)\left(\frac{13\,d_1 + 36\,d_2}{16\,d_1 + 48\,d_2}\right)$$

Three-phase, 1/3 to 2/3 pitch:

$$K_3 = 3\left(P - \frac{1}{3}\right)\left(\frac{13\,d_1 + 36\,d_2}{16d_1 + 4\,8\,d_2}\right) + 3\left(\frac{2}{3} - P\right)\left(\frac{7\,d_1 + 12\,d_2}{16\,d_1 + 48\,d_2}\right)$$

Two-phase, 1/2 to full pitch:—

$$K_3 = 2\left(P - \frac{1}{2}\right) + 2\left(1 - P\right)\left(\frac{5\,d_1 + 12\,d_2}{8\,d_1 + 24\,d_2}\right)$$

By letting $d_1 = 0$, that is, by assuming all the leakage flux passes above the coils, we obtain the equations for the three straight lines of Fig. 6:—

Three-phase, 2/3 to full pitch:— $K_3 = 0.75\,P + 0.25$
Three-phase, 1/3 to 2/3 pitch:— $K_3 = 1.5\,P - 0.25$
Two-phase, 1/2 to full pitch:— $K_3 = 1.0\,P$

By letting $d_2 = 0$, that is, by assuming all the leakage flux passes through the coils, we obtain the equations for the lower set of lines in Fig. 7, marked *A*.

For the average open slot stator, $d_1$ is nine times $d_2$, so that the three equations for $K_3$ now become

Three-phase, 2/3 to full pitch:— $K_3 = 0.61\,P + 0.39$
Three-phase, 1/3 to 2/3 pitch:— $K_3 = 1.22\,P - 0.016$
Two-phase, 1/2 to full pitch:— $K_3 = 0.812\,P + 0.188$

These values are plotted in Fig. 7, marked *B*, and are sufficiently accurate for all primary coil design work.

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4—"The Induction Motor", by Vickers. Page 311.
5—"Electrical Machine Design", by Gray. Page 220.
6—"Induction Motors", by Miles Walker. Page 68.
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Three-phase, 2/3 to full pitch:— $K_3 = 0.563\,P + 0.437$
Three-phase, 1/3 to 2/3 pitch:— $K_3 = 1.125\,P + 0.0625$
Two-phase, 1/2 to full pitch:— $K_3 = 0.75\,P + 0.25$

# Some Transmission Line Fundamentals (Concl.*)

C. A. BODDIE

## VELOCITY OF PROPAGATION

The velocity of propagation in most overhead lines is approximately equal to the velocity of light,—

$$V = \sqrt{\frac{1}{LC}} \qquad (15)$$

where $L$ = inductance per mile, $C$ = capacity per mile, $V$ = the velocity in miles per second. For lines other than overhead lines, such as cable or lines in which there is distributed series inductance, such as loaded telephone lines, open or cable, the velocity of propagation may be materially different from the velocity of light. In some cases this velocity may be as low as 10 000 miles per second. The fact that the velocity of propagation is not a constant, but is a variable depending upon the line constants, and that this may vary over such a wide range, is a matter of considerable interest.

## ELEMENTARY ANALYSIS OF PROPAGATION OF CURRENT ON THE LINE

The propagation of impulses, surges and disturbances in general on the power line are of considerable practical importance. An elementary view of the mechanism whereby a disturbance moves down a line may be helpful. Let the wires A and B Fig. 6 be the wires of a power line. Let the ordinates of the curve a, b, c represent the potential between the wires at a given instant and for the position at which the ordinate is drawn. Let the potential between the wires at point 1 be $e_1$ and the potential at point 2 be $e_2$. The difference of potential between these two points is $e_1 - e_2 = -\Delta e$, where the negative sign indicates decreasing voltage with increasing distance from the sending end.

If for simplicity the resistance of the line is neglected, the potential drop between two points is entirely represented by the inductive drop. The inductive drop between points 1 and 2 is due to the magnetic flux expanding from the center of the wires. The rate at which this flux cuts the wires determines the voltage drop. The coefficient of self inductance $L$ is a quantity which gives the flux which links one mile of circuit when one ampere flows in the wires. The flux which links the short length of the line $\Delta x$ per ampere of current is $L\Delta x$. If the current in this portion of the line is increased at the rate $\frac{di}{dt}$ amperes per second, then the counter e.m.f. of self induction or

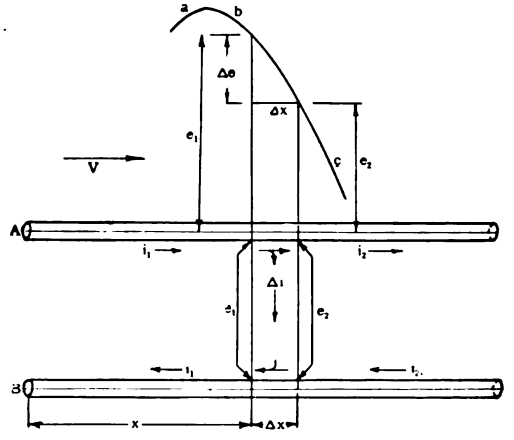


FIG. 6—A REPRESENTATION OF CURRENT MOVING ALONG A SHORT SECTION OF LINE

voltage drop across the element $\Delta x$ is given by,—

$$L\,\Delta x\,\frac{di}{dt}$$

equating this to $\Delta e$, gives,—

$$e_1 - e_2 = -\Delta e = L\Delta x\,\frac{di}{dt}$$

$$-\frac{\Delta e}{\Delta x} = L\,\frac{di}{dt}$$

If the distance between positions 1 and 2 is made very small $\frac{\Delta e}{\Delta x}$ may be written $\frac{de}{dx}$, whence,—

$$\frac{de}{dx} = -L\,\frac{di}{dt} \qquad (16)$$

The left hand expression $\frac{de}{dx}$ may be expressed

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as voltage drop per mile at the point in the line under consideration. The equation as a whole, states that the voltage drop per mile is equal to the coefficient of self-inductance multiplied by the rate of increase of line current measured in amperes per second.

In a similar way let the line current at positions 1 and 2 be represented by $i_1$ and $i_2$ respectively. The change in current is,—

$$i_1 - i_2 = -\Delta i$$

The current flowing into the section of line $\Delta x$ is $i_1$ and the current flowing out of it is $i_2$. The difference $\Delta i$ flows across from wire to wire. If it is assumed that the insulation of the line is perfect, i.e., there is no leakage, there can be no conduction current between wires. The only current which can flow therefore is a dielectric current, that is the current $\Delta i$ flows from wire to wire through the dielectric in the same way that current flows between the plates of a condenser. In this case the plates of the condenser are the two portions of the line included in the length $\Delta x$. The current flowing into a condenser is proportional to the capacity of the condenser and the rate of increase of voltage, that is,—

$$i = C \frac{de}{dt}$$

If $C$ is the capacity per mile between the two wires, then the capacity for the length $\Delta x$ is $C\Delta x$ and the condenser current is $C\Delta x \frac{de}{dt}$. Hence the loss in current in the line for the length $\Delta x$ is equal to the current which flows into the condenser formed by the line of length $\Delta x$, or,—

$$i_1 - i_2 = -\Delta i = C\Delta x \frac{de}{dt}$$

$$\frac{\Delta i}{\Delta x} = -C \frac{de}{dt}$$

and in the limit,—

$$\frac{di}{dx} = -C \frac{de}{dt} \quad \text{.....(17)}$$

This equation means that the rate of decrease of line current in amperes per mile is equal to the capacity per mile multiplied by the rate of increase of potential measured in volts per second.

In addition to the relation given by equation (16) and (17), the relation given in equation (9) holds for the current and voltage at any point in the line. It may be written,—

$$e = Z_0 i \quad \text{.....(18)}$$

Differentiating (18) with respect to $x$ and substituting the value of $\frac{de}{dx}$ in (16) we get,—

$$Z_0 \frac{di}{dx} = -L \frac{di}{dt} \quad \text{.....(19)}$$

Also differentiating (18) with respect to $t$ and substituting the value of $\frac{de}{dt}$ in (17) we get,—

$$\frac{di}{dx} = -C Z_0 \frac{di}{dt} \quad \text{.....(20)}$$

From (19) and (20) we get,—

$$Z_0 = \sqrt{\frac{L}{C}}$$

which has already been given in equation (11). It is a special case of equation (10) where the resistance and leakage are assumed to be zero.

If direct-current voltage is impressed on the line, a steady current will flow according to the relation.

$$i = \frac{e}{\sqrt{\frac{L}{C}}}$$

Take for example the case of a line consisting of two 4/0 copper conductors spaced 15 feet between centers. The inductance for one mile of line and return is 4.414 millihenries. The capacity between wires per mile is 0.00684 microfarads. The value of $Z_0 = \sqrt{\frac{L}{C}} = \sqrt{\frac{4.414 \times 10^{-3}}{0.00684 \times 10^{-6}}} = 804$ ohms. If a switch should be closed connecting such a line to a generator at the instant the generator voltage was, say, 100 000 volts, the current flowing into the line would be,—

$$i = \frac{e}{Z_0} = \frac{100\ 000}{804} = 124.4 \text{ amperes}$$

The amount of power flowing into the line at this instant is,—

$$W = e \times i = 100\ 000 \times 124.4 = 12\ 440\ kw.$$

If the line were of infinite length, and the 100 000 volt potential were maintained constantly at the generating end, the current of 124.4 amperes would flow into the line continuously.

As the current wave advances down the line various parts of the line are progressively raised from zero potential to full line potential. In doing this, energy is stored in the magnetic field surrounding the wires and in the electric field between the wires. The energy per mile stored in the electric field is given by:—

$$W_s = 1/2\ Ce^2 \quad \text{.....(21)}$$

The energy stored in the magnetic field is given by,—

$$W_m = 1/2\ Li^2 \quad \text{.....(22)}$$

The ratio of these two energies is,—

$$\frac{W_s}{W_m} = \frac{C}{L} \times \frac{e^2}{i^2} \quad \text{.....(23)}$$

Since at every instant the current and voltage are related according to equation (18), we have,—

$$\frac{e^2}{i^2} = Z_0^2 = \frac{L}{C} \quad \text{.....(24)}$$

Substituting this value in (23), gives,—

$$\frac{W_s}{W_m} = \frac{C}{L} \times \frac{L}{C} = 1 \quad \text{.....(25)}$$

Hence the energy stored in the electric and magnetic fields are equal.

### REFLECTIONS AT OPEN END

If the line under consideration, instead of being of infinite length, is open at the distant end, then the current as calculated above will not flow steadily into the line. At the instant the switch is closed, current will rush into the line as calculated above. This current will flow down the line until the end is reached.

During this time the energy from the generator was used in charging the line, and was stored equally in the magnetic and electric fields. At the instant the

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wave reaches the end of the line, and immediately thereafter, the generator still continues to deliver energy just as though nothing had happened, since at this instant no effect due to conditions existing at the open end can be transmitted back to the generator. The result is that energy in the form of an electric current is fed into the line in the region of the open end and, since there is no place for this current to flow, there must be an increase in the quantity of electricity per unit length at the end of the line. Since the potential is determined by the charge per unit length, it follows that the potential must rise. This rise in potential will produce a flow of current from the end of the line back toward the generator, since the potential between the wires at the end of the line exceeds that at the generating end. The value of the current flowing back toward the generator is equal to the excess potential at the end of the line divided by the characteristic impedance. Since the current at the open end must be zero, the reflected current must equal the forward current. The general relations between the current and voltage in the advancing and reflected waves are,—

$$e_n = Z_0 i_n \quad \ldots\ldots (26)$$

$$e_r = - Z_0 i_r \quad \ldots\ldots (27)$$

For the reflected wave the total potential at any

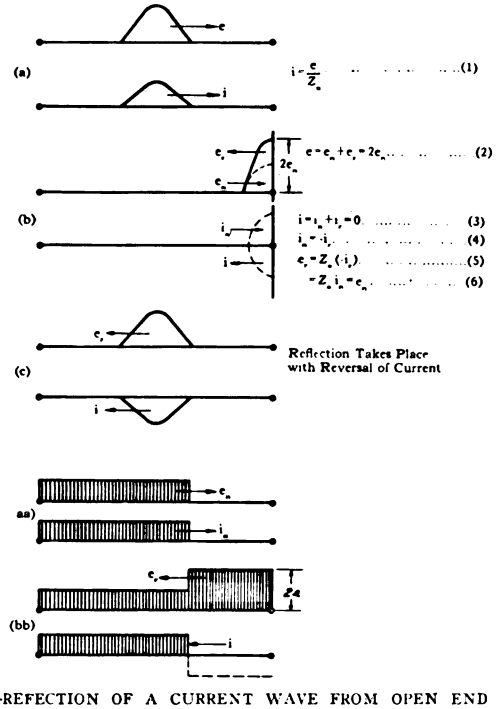


FIG. 7—REFECTION OF A CURRENT WAVE FROM OPEN END OF LINE

instant after reflection is equal to the sum of the potentials of the advancing and reflected waves, or,—

$$e = e_n + e_r \quad \ldots\ldots (28)$$

Also the total current in the line after reflection is equal to the sum of the advancing and reflected currents, or,—

$$i = i_n + i_r \quad \ldots\ldots (29)$$

Since the current at the end of the line must be zero when the line is open, we have,—

$$i_n + i_r = 0 \quad \ldots\ldots (30)$$

Hence,—

$$i_r = - i_n \quad \ldots\ldots (31)$$

or the reflected current is equal to the advancing current in magnitude, but the direction of flow is reversed. Substituting the value of $i_r$ in equation (27), gives,—

$$e_r = Z_0 i_n = e_n \quad \ldots\ldots (32)$$

That is, the reflected wave of potential is equal in value to the advancing potential wave and it is also of

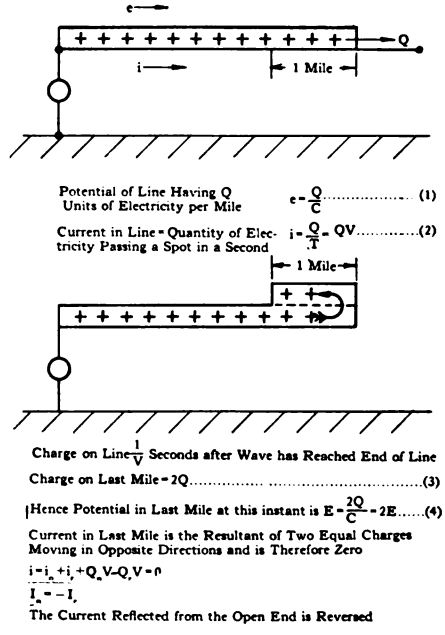
e
Q
i
1 Mile
Potential of Line Having Q Units of Electricity per Mile e = Q/C (1)
Current in Line = Quantity of Electricity Passing a Spot in a Second i = Q/1 = QV (2)
1 Mile
Charge on Line 1/V Seconds after Wave has Reached End of Line
Charge on Last Mile = 2Q (3)
Hence Potential in Last Mile at this instant is E = 2Q/C = 2E (4)
Current in Last Mile is the Resultant of Two Equal Charges Moving in Opposite Directions and is Therefore Zero
i = i_n + i_r + Q_nV - Q_rV = 0
I_n = - I_r
The Current Reflected from the Open End is Reversed

FIG. 8—A RECTANGULAR CURRENT WAVE REFLECTED AT OPEN END OF LINE

the same polarity. Substituting this value of reflected potential in equation (28) gives,—

$$e = e_n + e_r = 2e_n \quad \ldots\ldots (33)$$

or, the total line potential immediately after the wave reaches the end of the line is just twice the normal potential of the advancing wave.

The condition of things in a line open at the distant end is shown graphically in Fig. 7. At (a) is shown the advancing potential and current waves assuming an impulse whereas (aa) shows the condition when the voltage is applied steadily. The advancing potential wave is shown as $e_n$, the advancing current wave is shown as $i_n$. Fig. 7 (b) shows the condition at the end of the line at the instant of reflection. The normal or advancing current wave is neutralized by the reflected current wave, giving zero current at the end. The reflected potential adds directly to the normal potential giving double voltage. In Fig. 7 (bb), which applies to the case of a continually applied generator voltage, the reflected potential wave applies double-voltage to the line as it proceeds backward toward the generator. The reflected current wave however, being of opposite polarity, neutralize the advancing current wave, leaving zero current in the line between the end of the line and the reflected wave front. At (c) is shown the reflected waves of impulse as they return to the generating end. The reflected potential wave $e_r$ is of the same magnitude and polarity as in the original advancing wave. The reflected current wave

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is also of the same magnitude as the advancing current wave, but the direction of the current as well as the motion are reversed.

In Fig. 8 is shown another way of looking at the same phenomena as Fig. 7. For simplicity only one wire

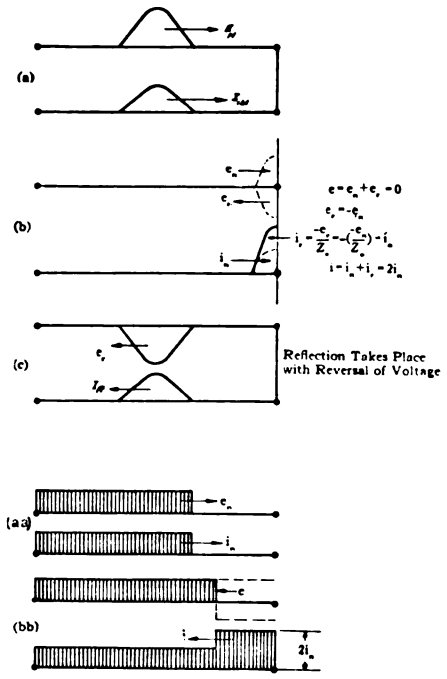


FIG. 9—REFLECTION OF A CURRENT WAVE FROM CLOSED END OF LINE

is considered, and the generator is assumed to energize this wire to a positive potential. This is accomplished by feeding positive charges into the line. In order to bring the line up to the potential $e$, $Q$ units of electricity must be applied to each mile of line according to the relation,—

$$e = \frac{Q}{C} \quad \text{.....(34)}$$

The current in the line is equal to the quantity of electricity passing a point in one second, or,—

$$i = \frac{Q}{T} \quad \text{.....(35)}$$

where $T$ is the time required to travel one mile, or,—

$$i = QV \quad \text{.....(36)}$$

where $V$ is the velocity of wave. The line is charged uniformly to full potential the entire distance from the generator to the advancing wave front, and throughout this distance a steady current $i$ flows.

When the advancing wave or system of positive charges reaches the end of the line, the advancing wave feeds into it $Q$ units of electricity in the time required to travel one mile just as it did before the end was reached. Thus there exists on the mile of line at the end, twice as many units of electricity after reflection as before. The potential of the line immediately goes to double potential, since there is twice the charge per unit length. It will be noticed that after reflection there is a forward motion of positive charges at the end of the line and an equal reversed motion of positive charges. Since current flow is determined by the total charge passing a point per second, these two effects completely neutralize each other, giving zero current between the end of the line and the returning wave front. This agrees with (b) of Fig. 7.

REFLECTION AT CLOSED END OF LINE

Fig. 9 shows the condition involved in the reflection of a wave at the closed end of a line. The advancing current and potential waves are shown at (a) $e_n$ being potential and $i_n$ current. Since the line is closed at the end there can be no potential at this point. From equation (28) the sum of the advancing and reflected potentials must equal zero, or,—

$$e_n + e_r = 0 \quad \text{.....(38)}$$

Hence,—

$$e_r = -e_n \quad \text{.....(39)}$$

That is the reflected potential wave is of the same magnitude but of opposite polarity to the advancing wave. The current at the closed end is the sum of the reflected and advancing currents as given in equation (29). The reflected current wave is obtained from equation (27) as,—

$$i_r = -\frac{e_r}{Z_0} = -\left(\frac{-e_n}{Z_0}\right) = i_n \quad \text{.....(40)}$$

That is the reflected current wave is of the same polarity as the advancing current wave. The total current at the end of the line therefore is,—

$$i = i_n + i_r = 2i_n \quad \text{.....(41)}$$

Hence the current at the end of a closed line during reflection is double the normal current. This is shown

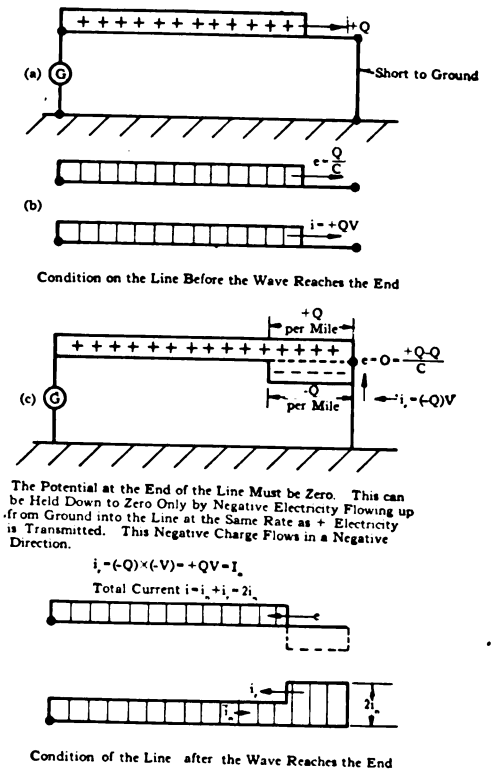
+Q
(a)
G
Short to Ground
e=Q/C
(b)
i=+QV
Condition on the Line Before the Wave Reaches the End
+Q per Mile
e=0=+Q-Q/C
(c)
-Q per Mile
i=-(-Q)V
The Potential at the End of the Line Must be Zero. This can be Held Down to Zero Only by Negative Electricity Flowing up from Ground into the Line at the Same Rate as + Electricity is Transmitted. This Negative Charge Flows in a Negative Direction.
i=(-Q)×(-V)=+QV=I
Total Current i=i+i=2i
Condition of the Line after the Wave Reaches the End

FIG. 10—A RECTANGULAR CURRENT WAVE REFLECTED FROM CLOSED END OF LINE

at (b) Fig. 9. Under reflection from the closed end, the current and voltage waves move back toward the generator, the current being of the same amplitude and polarity as the original advancing wave, but the potential wave being reversed.

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The condition for the reflection at the closed end when the applied potential is held constant is shown at (aa) and (bb) Fig. 9.

The phenomena of reflection at the closed end of the line may also be analyzed as shown in Fig. 10, which is similar to Fig. 8. At (a) the generator is shown feeding positive charges into the line, which is short-circuited to ground at the distant end. The potential and current waves are shown at (b). At (c) are shown the conditions just after reflection at the closed end, which, being connected to ground, is held down to zero potential. When the positive charges comprising the advancing wave front reach the end of the line they try to raise it to the line potential. Negative electricity, however, flows up from the ground through the ground connection in an amount sufficient

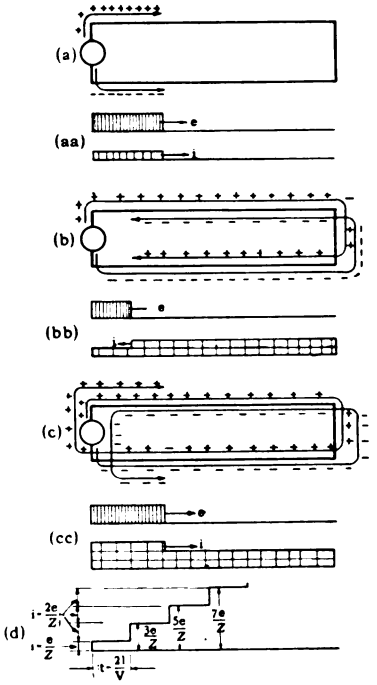


FIG. 11—HOW A SHORT-CIRCUIT CURRENT IS BUILT UP IN A LINE

to neutralize exactly the positive charge per unit length arriving on the wave front. This flow of negative electricity begins at the instant the wave front reaches the ground connection. The potential at the end of the line is reduced to zero, and the effect spreads back toward the generator, thus forming a wave or flow of *negative* electricity toward the generator of the same strength as the original flow of positive electricity from the generator. The region between the end of the line and the returning wave front contains advancing positive electricity and returning negative electricity. Since a reverse flow of negative electricity is the same as a forward flow of positive electricity, the effect is additive, resulting in double current in the region between the end of the line and the returning wave front. This is shown at (d) Fig. 10, where the current is shown double and the voltage is reduced to zero.

### HOW A SHORT CIRCUIT BUILDS UP

It is of interest to follow the process whereby a short-circuit current is built up in a line. The current does not flow instantly according to Ohm's law, but is built up by a process of reflections until the steady state determined by Ohm's law is finally reached. The early stages of the process are indicated in Fig. 11, where (a) shows a generator wave of positive electricity in one wire and a corresponding wave of negative electricity in the other wire. The current and voltage are normal in the advancing waves. At (b) is shown the condition after reflection at the short-circuited end, but before reaching the generator. There is double current in both wires from the end of the line back as far as the returning wave front, as shown at (bb), due to the forward flow of positive electricity and reverse flow of negative electricity in the top wire, and a corresponding condition in the bottom wire. At (c) is shown the condition after the returning waves from both wires have reached and passed through the generator. The positive wave coming in on the negative wires passes through the generator, entering at the negative pole and leaving by the positive pole, continuing to flow on into the positive conductor. Work is done by the generator on this flow of positive electricity between its terminals, equal to the current multiplied by the voltage. Similarly the flow of negative electricity returning to the generator by way of the positive conductor flows through the generator armature, entering the positive pole of the generator and leaving by the negative, continuing to flow on into the negative conductor. Work is also done by the generator on this stream of negative electricity equal to the product of the current by the generator potential. After passing through the generator the positive conductors are carrying an advancing stream of positive charges and the negative conductor an advancing stream of negative charges, thus exactly reproducing the condition as shown at (a) so far as the advancing waves are concerned. There is this difference, however, that the conductors beyond the wave front are all carrying double current and the new advancing wave adds its effect on top of this making a total current in the conductors between the generator and the wave front of three times normal. This condition is shown at (cc). The potential condition of the conductors is exactly the same as for the original wave shown at (a). The waves as shown in condition (c) flow to the end of the line and are reflected, repeating the condition as shown at (b). Returning again to the generator the wave passes through it and repeats the condition (c) except that the currents are always added to the pre-existing currents. The net result is that the current increases by steps as shown at (*d*), which represents the progressive rise of current in the generator armature. The initial current issuing from the generator is,—

$$i = \frac{e}{Z_0}$$

This continues to flow from the generator steadily until the positive charges have gone out over the posi-

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tive conductor, and returned by way of the negative conductor, and negative charges have gone out over the negative conductor and returned by way of the positive conductor, thus having gone through twice the length of the line. The time required is therefore $\frac{2l}{V}$. The current in the generator now rises by an amount equal to $\frac{2e}{Z_0}$ making a total current of $\frac{3e}{Z_0}$. This continues to flow for a time again equal to $\frac{2l}{V}$. Then the current again rises by an amount equal to $\frac{2e}{Z_0}$, making a total of $\frac{5e}{Z_0}$. If there were no resistance in the line this process would continue indefinitely and the current would build up to infinity.

The reason the current does not go to infinity is because of the resistance of the conductor. The effect of resistance is shown by the fact that the potential along the line is not constant, as has been assumed in the foregoing analysis, but is reduced by the ohmic drop. For instance at the moment when the reflected wave has just reached the generator the potential between the line terminals is not zero, but is equal to the *ri* drop in the line. The current wave which flows into the line from the generator is always equal to the unbalanced generator potential divided by the characteristic impedance. Since the *ri* drop at the line terminals in effect raises the voltage of the line, the generator has only the excess voltage $e - ri$ available for driving current into the line, and the current flowing into the line at this instant is equal to,—

$$\Delta i = \frac{e - ri}{Z_0} \qquad (42)$$

This is a general relation where $\Delta i$ represents the increase in current flowing into the line at the instant of reflection at the generating end, and $i$ is the total current in the line at the instant of reflection, $r$ being the total resistance. The time between reflections is the time required to travel twice the length of the line. We may therefore write,—

$$\Delta t = \frac{2l}{V} \qquad (43)$$

Dividing equation (42) by (43), gives,—

$$\frac{\Delta i}{\Delta t} = \frac{V}{2lZ_0}(e - ri) \qquad (44)$$

Since these increments of current and time are relatively small as compared with the final current and time, they may be treated as differentials. Hence,—

$$\frac{di}{dt} = \frac{V}{2lZ_0}(e - ri) \qquad (45)$$

$$\frac{di}{\left(\frac{e}{r} - i\right)} = \frac{Vr}{2lZ_0}dt \qquad (46)$$

integrating (46),—

$$-\log\left(\frac{e}{r} - i\right) = \left(\frac{Vr}{2lZ_0}\right)t + C \qquad (47)$$

where $C$ is a constant of integration. To determine this constant, note that when $t = O$, $i = O$. Hence,—

$$-\log\frac{e}{r} = C.$$

Substituting this value in equation (47) gives,—

$$\log\left(\frac{\frac{e}{r}}{\frac{e}{r} - i}\right) = \frac{Vr}{2lZ_0}t \qquad (48)$$

putting (48) in exponential form gives,—

$$\frac{\frac{e}{r}}{\frac{e}{r} - i} = \epsilon^{\frac{Vr}{2lZ}t} \qquad (49)$$

Solving (49) for $i$ gives,—

$$i = \frac{e}{r}\left(1 - \frac{1}{\epsilon^{\frac{VR}{2Z}t}}\right) \qquad (50)$$

Where $R$ is the resistance per mile of line, $V$ is the velocity of propagation and $Z_0$ the characteristic impedance. This equation gives the current at instant of time $t$. The final current is determined by Ohm's law $i = \frac{e}{r}$, since the exponent becomes infinity and the second term in the parenthesis reduces to zero. If a time is selected that

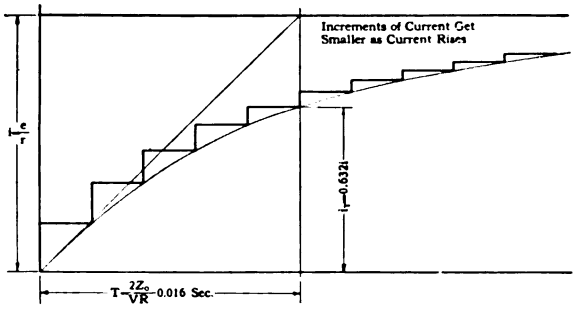


FIG. 12—THE RATE OF RISE OF CURRENT
In a transmission line of 4/0 wire and characteristic impedance of 804 ohms.

the exponent becomes unity, the current at this time becomes,—

$$i = \frac{e}{r}\left(1 - \frac{1}{\epsilon}\right) = 0.632\frac{e}{r} \qquad (51)$$

This time is determined as,—

$$t = \frac{2Z_0}{VR}$$

which is called the time constant. It is interesting to note that the time constant is independent of the length of the line, being a function only of the characteristic resistance, the velocity of propagation and the resistance per mile of line.

As an example, take the case of the 4/0 line whose conductor spacing is 15 feet, giving a characteristic impedance $Z_0 = 804$ ohms. The direct-current resistance per mile of line $R = 0.54$ ohms. The time constant as determined by equation (51) is,—

$$T = \frac{2 \times 804}{186\,000 \times 0.54} = 0.016 \text{ seconds}$$

This is shown in Fig. 12 where $= \frac{e}{r}$ gives the final value to which the current will rise. The current rises in steps as previously described, but follows the outline of the logarithmic curve expressed in equation (50). It rises to 0.632 of its final value in a time equal to its time constant, in this case 0.016 seconds. The initial rate of rise is such that if its advance continued, it would reach final current in a time equal to the time constant, or 0.016 second.

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# Unusual Vibration of a 25 000 Kw Turbine

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GREAT advances have been made in the past few years in the vibration problem as encountered on turbine-generator installations. Sensitive dynamic-balancing machines have been developed with capacities up to 125 tons, permitting balancing tolerances of the order of one-half in.-oz. per 1000 pounds of rotor. The heretofore complex analytical methods of correcting for balance have been reduced to simple, routine shop processes.

A further advance has been accomplished in the problem of balancing rotors in operation under their normal speed and temperature conditions, which may not always coincide with the cold, slow-speed balance in the dynamic machines. These processes have been made possible through the development of vibration instruments which indicate amplitudes and directions of vibration, and also the phase relation between the vibration and the rotating element. Analytical and graphical methods have been devised, employing this data to compute the location and amount of the unbalanced forces in a minimum of trials. It is now possible to compute both the amount and location of the necessary correction by data obtained on one trial run for each end, under ideal conditions.

Occasionally, however, vibration is encountered which does not respond to these modern methods. Investigations are then necessary to determine resonance possibilities in portions of the unit, or the structure as a whole, which may be a permanent characteristic or a transient phenomenon brought into play through temperature or loading changes, etc. It is also in order to include an investigation of the rotating elements themselves as regards heat distortion, journal flats, bearing clearances, gland strip rubs, etc. These studies usually disclose the trouble, the correction of which makes routine balancing possible.

An outstanding case of abnormal vibration, which was baffling in the extreme, occurred on a 25 000 kw installation. A type of vibration was encountered having characteristics so unusual that it is believed a description of the conditions met with and the ultimate cure may be of general interest.

The turbine is of the semi-double flow type with double exhaust, the bearings being supported by the exhaust cylinders, and the cylinders mounted on chairs, supported by the bedplate. The trouble was localized in the turbine, the generator having no part in the vibration.

The unit had given trouble from the start by vibrating badly at certain loads and on load changes. A great amount of balancing had been attempted, with practically no success. The installation of flexible connections at the exhausts and the equilibrium pipe, to eliminate the possibility of distortion had no effect. The spindle was dismantled, stronger bolts installed, press fits altered, and then put through severe heat tests while in the dynamic balancing machine. These tests showed the spindle to be stable under conditions more severe than existed in service. When the unit was reassembled after these alterations, its behavior was even worse than before. This was the situation in the spring of 1925.

At this time, vibration indicating apparatus had been developed by which the amplitudes of vibration could be determined very accurately, and also apparatus

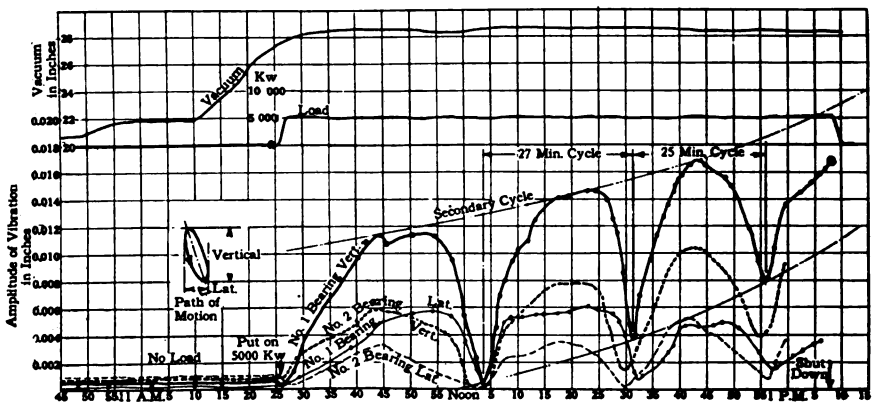


FIG. 1—VIBRATION CURVES ON NOS. 1 AND 2 BEARINGS, IN THE VERTICAL AND LATERAL DIRECTION, SHOWING CYCLIC CHANGES

which indicated the phase relation of the vibration to a datum on the rotating element.

With the aid of these instruments, an investigation of the vibration encountered after reassembling was carried out. Balancing by methods based on amplitudes and lag angles resulting from trial balance weights was attempted, but at the outset the amplitudes and scribed high spots were so erratic and changeable that further efforts in this direction were considered hopeless. It was then noticed that although the vibration was changeable, it was increasing and decreasing in some definite sort of periodic fashion. Observations in the vertical and lateral directions at both bearings were then made at about one minute intervals for several hours to explore these variations. These vibration amplitudes plotted on a time base exhibited the remarkable appearance shown in Fig. 1. The path of vibratory motion took the form of a narrow ellipse, with the major axis inclined slightly from the vertical, giving rise to the vertical and lateral components observed.

The unit ran quite smoothly when synchronized without load, but immediately after a load of 5000 kw

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was put on, the amplitudes of vibration commenced a cyclic variation having a period of about 25 minutes. For a very brief moment the engine was quite motionless once a cycle. The peak amplitudes were large and of several minutes duration. On this particular run, each succeeding maximum appeared to be growing greater and greater until it was advisable to shut the unit down. On later runs, however, it developed that this growth of the maximum vibration itself reached a

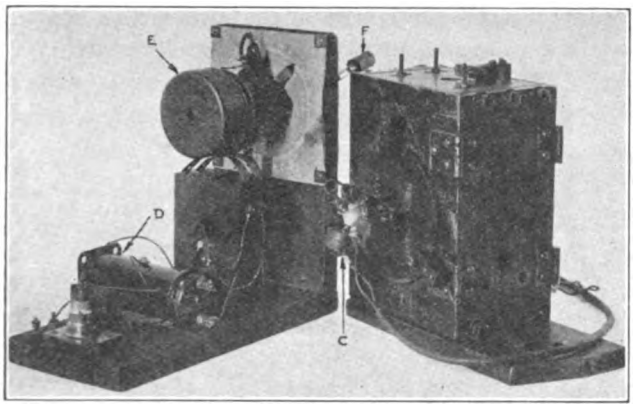


FIG. 2—VIBRATION PHASOMETER APPARATUS

maximum value followed by successively decreasing cycles until a minimum was reached. In other words, there existed a periodic phenomenon of a second order, of several hours duration.

It was at once noticed that these time curves were not sinusoidal, but more nearly cycloidal in shape. This later suggested a clue to their nature. The vibration phase-indicating apparatus was then set up to find if the lag angle was likewise subject to cyclic changes.

This apparatus, substantially as shown in Fig. 2, consisted of a microscope mounted on a heavy pendulum as the steady point, having as the objective etched cross lines on a glass slide held in a frame mounted on and vibrating with the bearing. The objective was illuminated by a neon lamp *C* flashing once a revolution by means of a spark coil *D* actuated by an interruptor device *E* attached at the end of the rotor shaft *F*. By rotating the graduated interruptor frame, the flash could be made to occur at any desired instantaneous spindle position. Thus, the instantaneous position of the spindle coincident with say, the upper maximum extremity of the vibratory motion was readily determined. This did not directly indicate the position of unbalance because of lag, but gave an index of this position. That is, if the position of unbalance changed, the index changed a like amount. Accuracy within about four degrees was realized. The indications of the vibrometer could be estimated to 0.0001 inch.

Both amplitude and lag-index observations were then made simultaneously, and as rapidly as possible.

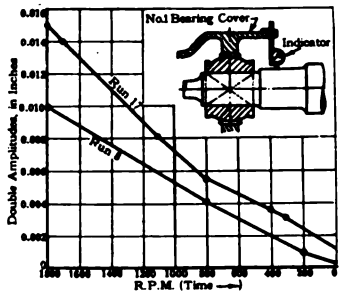


FIG. 4—RELATIVE MOVEMENTS BETWEEN NO. 1 BEARING COVER AND SHAFT AT GLAND SPACE

Observed in the attempt to measure shaft deflection on shutting down during a rough period.

It was found that the index did not jump from point to point, but rather was undergoing a continuous creeping. It should be noted that the inclination of the axis of the elliptic path of vibration did not change nor rotate, as is often encountered on installations having variable elastic characteristics. On the first test run the remarkable fact developed that during the interval required for the vibration amplitudes to vary from one minimum to the next, the lag-angle crept forward with rotation exactly 360 degrees. The data plotted on a time base is shown in Fig. 3. Further investigation proved that the maximum and minimum points on the amplitude curve always agreed with definite lag-angles practically 180 degrees apart.

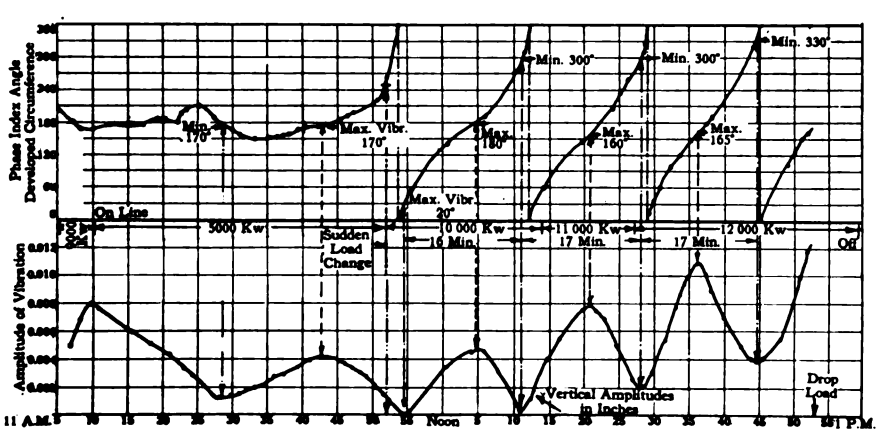


FIG. 3—VIBRATION AMPLITUDES AND PHASE INDEX ANGLES OBSERVED CONCURRENTLY

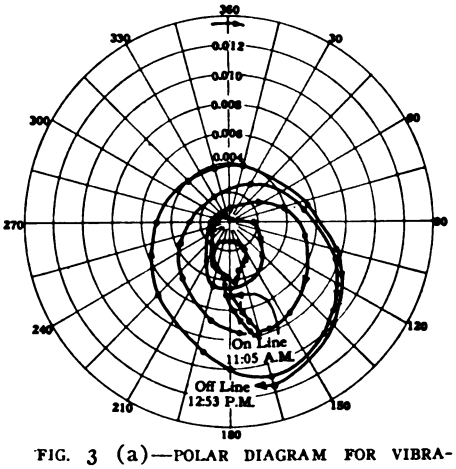


FIG. 3 (a)—POLAR DIAGRAM FOR VIBRATION CURVE OF FIG. 3

On this and later runs, it appeared that a load change was necessary to start the cycles. When synchronized and running without load, or with very small load, the unit operated very smoothly with no cyclic

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vibration nor regular angular variations. After a load increase of 5000 kw or more, the definite cycles started. The periods for different runs varied from about 15 to 25 minutes, and apparently were affected in some way by the amount and position of balance weights. For a given run after the first two cycles, the period was fairly constant—in fact, after timing a few cycles, it was possible to predict just what phase of vibration the turbine would be going through some hours ahead. Once having set in, the cycles could not be changed by any variation of the operating conditions.

oil temperature or pressure was found which might be connected with the phenomena.

Mechanical movements were investigated at many points, both by levels and dial indicators, to find if any periodic distortion existed, with a negative result. The possibility of variations at the coupling which might be brought about by variable torque on badly fitted coupling pins was investigated. In short, neither cause nor any secondary effect could be found to throw light on the trouble.

It was found, however, that when the unit was

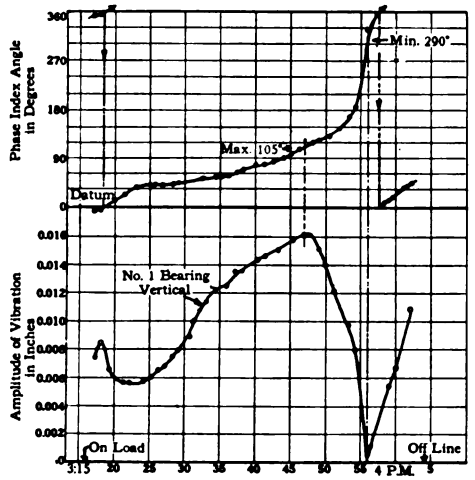


FIG. 5

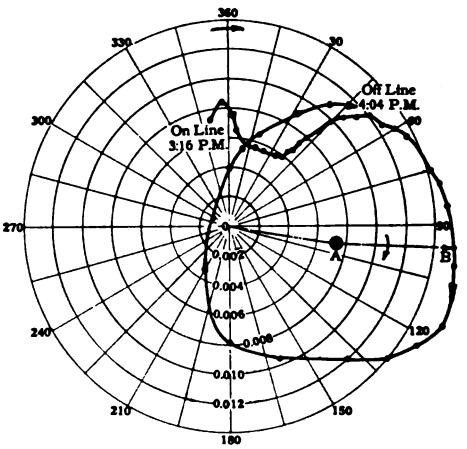


FIG. 5 (a)

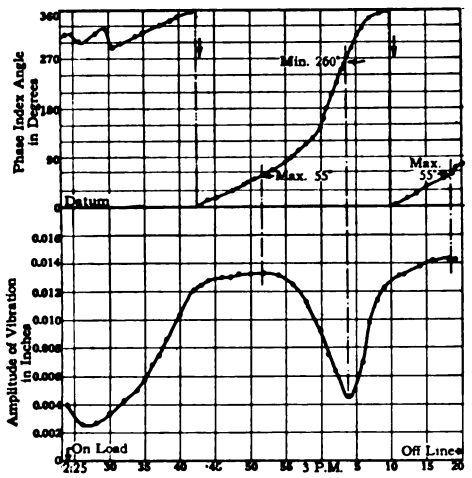


FIG. 6

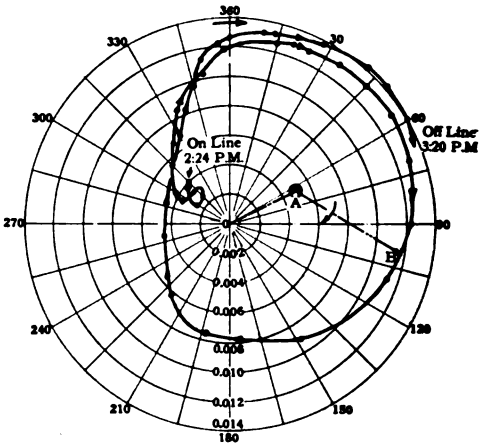


FIG. 6 (a)

FIGS. 5 AND 6—TYPICAL VIBRATION CURVES OF THE CONTINUOUSLY ROTATING TYPE AND THE CORRESPONDING POLAR DIAGRAMS

Naturally a great amount of coincident observation was carried out in the attempt to correlate the cyclic phenomena with some external cause. Raising and lowering the system frequency had no effect. The cycles occurred both when the unit was carrying the load alone and when tied in with other units. There was no other rotating machinery nearby running anywhere near 1800 r.p.m. to cause beats which might account for the periodic variation. However, beats would have given rise to a sinusoidal graph, whereas the fluctuations had a definite cycloidal nature. No periodic fluctuations in either load, steam pressure or temperature, vacuum, bleeding, gland water pressure, shut down during a rough spell, the spindle shaft at the thrust end appeared to be bent, straightening as the speed became lower. It was not possible to take off load and drop speed precisely at the instant of minimum vibration, because of the very short duration of this condition, but the indications were that the apparent bend was in proportion to the amount of vibration. The shaft bend was determined by a dial indicator mounted on the bearing in the vertical direction and touching the shaft. This was not entirely reliable, as the observed movement would be affected by the phase difference between the vibratory motion of the bearing cover and that of the spindle. In Fig. 4 are shown

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apparent shaft deflections on dropping speed.

Changes in balance weights were then tried to find the effect of changes in unbalance on the magnitudes of the peaks of vibration. A new feature developed with a certain change in weight, the lag-angle positions did not continuously rotate as before, but oscillated between two definite positions about 90 degrees apart. The vibration had the same periodic character and the angular oscillations corresponded exactly with the vibration periods. Figs. 5 and 6 are typical of the continuously rotating type, and Figs. 7 and 8 show runs having angular oscillation. These runs represent trials with various balance weights. The lag index and amplitudes are plotted on the same time base.

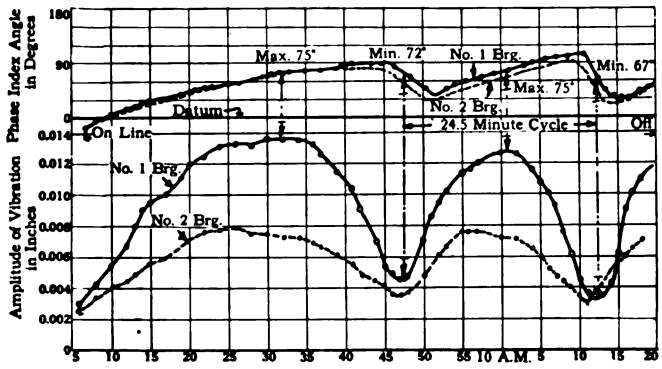


FIG. 7

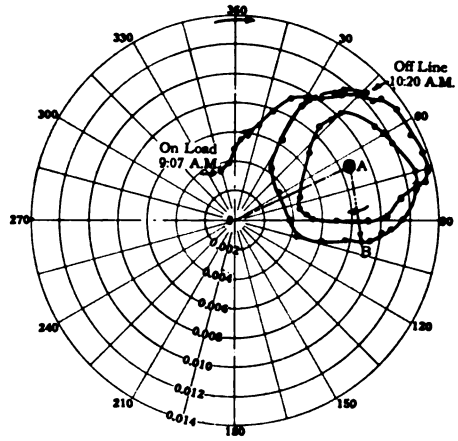


FIG. 7 (a)

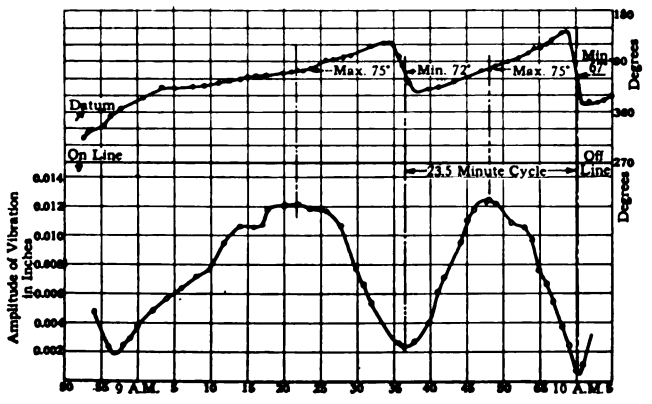


FIG. 8

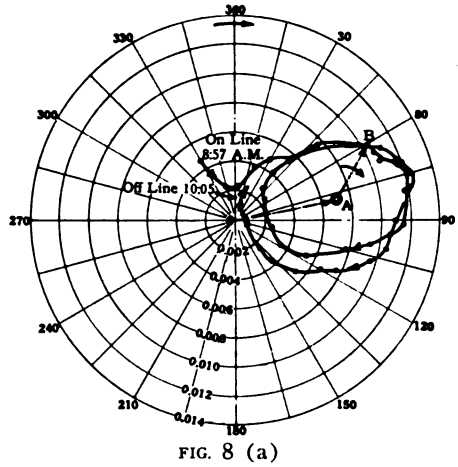


FIG. 8 (a)

FIG. 7 AND 8—TYPICAL VIBRATION CURVES OF THE OSCILLATING TYPE AND THE CORRESPONDING POLAR DIAGRAMS

It was thought at first that a new condition existed for the oscillating case, but it was later found that the two cases were identical. Further observations showed that on a given run, this oscillating lag position phenomenon, after a few cycles, usually changed suddenly into the complete rotation type. Fig. 3 was such a run, and in Fig. 8 one more cycle would probably have gone into the continuous rotation type.

A further feature was observed:—the lag angle changed slowly during the period of maximum vibration, and rapidly at the moment of minimum vibration. This was true for both types of angular change.

By this time the idea was suggested that there existed a "travelling" rotating unbalance in conjunction with a fixed unbalance relative to the spindle. When the two coincided, the vibration was at its maximum, and when on opposite sides, the minimum vibration resulted. In Fig. 9, two ideal cases are shown, combining vectorially a fixed unbalance with a greater rotating unbalance for Case 1, and with a lesser rotating unbalance for Case 2. The resultants for the various positions of the continuously moving unbalance fall on the locus circles as shown. Assuming the angular movement to be continuous and uniform, the angular change of the resultant was plotted (b) and (e) and also the corresponding unbalance, (c) and (f). The unbalance-time curves for both cases are similar, but the angle-time curves for Case 1 show the continuous rotation, and for Case 2 the oscillating feature. The difference is merely in the proportion of the rotating to the fixed unbalance. The similarity between the ideal curves and those made from actual observations is self-evident.

The correlation between angles and amplitudes naturally led to plotting amplitudes against angles on a polar chart, irrespective of time. Figs. 3 (a), 5 (a), 6 (a), 7 (a) and 8 (a) corresponding to the respective time curves, were the result. The curves definitely took the shape of eccentric circles.

The deduction appeared obvious. The theory of a fixed and a steadily rotating unbalance completely satisfied the nature of the phenomenon observed. As-

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suming vibration amplitudes are a measure of the amount of unbalance, the plotted figures actually show the relation between the two types of unbalance. Points on the curve virtually represent positions of mass centers of the spindle.

The center of the plotted circle then represents the location of the "stationary" unbalance, and its distance to the center of the polar diagram represents the amount of this unbalance. Then, the radius of the plotted figure represents the amount of the rotating unbalance, the vector sweeping around the circle as its position changes.

If the rotating unbalance is less than the stationary, the pole is outside of the locus circle, and the angular index oscillates through an angle limited by the tangents to this circle. But if the plotted figure includes the polar center, then the angular index rotates continuously. Thus, where the figure is near the polar center, the angular change is very rapid, as was observed.

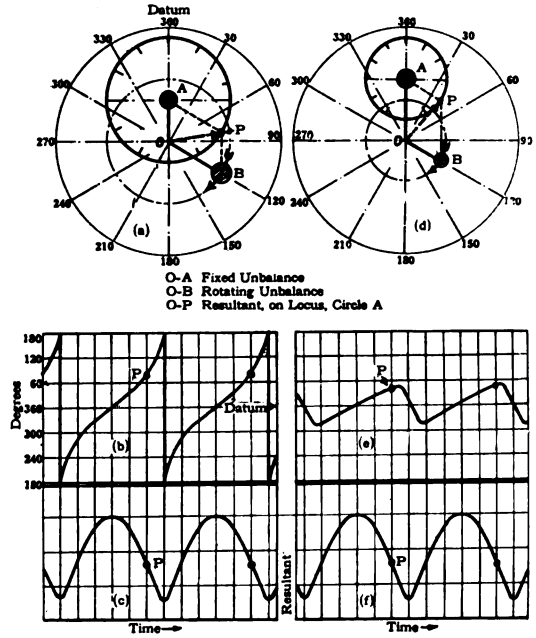


FIG. 9—IDEAL CURVES OF RESULTANT UNBALACE (AMPLITUDES) AND POSITION OF RESULTANT VECTOR FOR A COMBINATION OF A FIXED AND A STEADILY ROTATING UNBALANCE

Case 1—*B* greater than *A*
Case 2—*B* less than *A*

On the runs showing a transition from the oscillatory angular movement to the continuous rotation, the rotating unbalance either grew or the stationary unbalance lessened until the circular figure included the polar center. The secondary period wherein the successive vibration peaks waxed and waned is represented by the figure expanding and contracting, in the form of a spiral. Fig. 3 (a) shows this feature clearly. The curious migrations of small amounts prior to the commencement of the circular travel represent the fairly uniform vibration when running at a small load or on no load before the load increase which instituted the periodic phenomena.

From these studies, it appeared to be possible to balance out the stationary unbalance, leaving only the rotating component. This would result in a continuous vibration of some constant amount, without cycles. The changes in balance weight positions had already brought a response in changing the position of the centers of the plotted figures. It is theoretically possible to calculate the location and amount of unbalance by either the angular change or amplitude change resulting from two test runs with known trial weights, or by one test run using both angle and amplitude data.

Accordingly, the correction as computed was applied. The result at the beginning of the run was very promising, the fixed unbalance having been reduced to a small proportion of the rotating, and the resultant not excessive. But, after a few cycles, the rotating unbalance appeared to grow, dragging the stationary unbalance with it into the secondary cycle, as exhibited by the spiral form of the curve. The vibration soon became large. The inference was that the condition of balance was unstable.

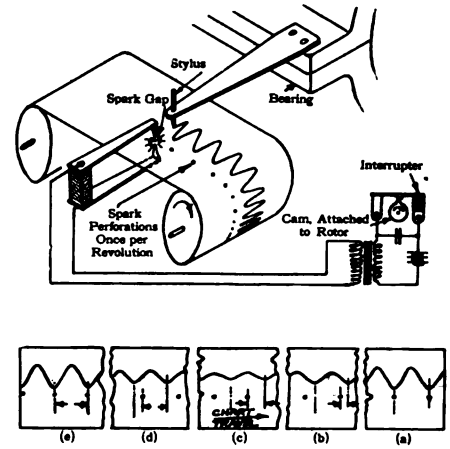


FIG. 10—SCHEMATIC ARRANGEMENT OF VIBRATION AND ROTATION RECORDING DEVICE

Representation of chart covering one full cycle, showing lag of rotation behind vibration at various stages.

It appeared impossible to avoid the conclusion that the fault lay within the spindle. An explanation was advanced that a flaw or other weakness existed in the metal of the spindle body, or in the joint between the middle body, and the end section of the spindle. This, combined with the vibratory reactions at the bearings, or with a gravity influence, was imagined to produce a rotational creeping of a bend in the spindle. The possibility of gyroscopic disturbances, such as sometimes occur with loose hubs, was also considered.

If the periodic spells had been due to a beat phenomenon, the assumption of a second disturbing agency was necessary. The rotational speed was 1800 r.p.m., and the periods averaged about 25 minutes. Therefore, the two disturbances would have a ratio of 45 000 to 45 001. Such close tuning was unthinkable. On the other hand, assuming a moving bend in the spindle, the rate of creeping would be of the order of 0.008 of one degree per revolution. This did not seem illogical.

To verify the fact that the vibration was not in step with rotation, a rough type of vibrograph was

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made up on the job to record the turbine vibration on a moving chart with a stylus, as represented in Fig. 10. An electrical contact breaker device was attached to the spindle, interrupting the circuit once a revolution at a fixed spindle position. An induction coil in this circuit then produced a spark once a revolution. The secondary leads were arranged immediately next the stylus writing the vibration wave, so that the spark perforated the chart at this point.

Records were then made extending over several of the periods of vibration; illustrated by Fig. 10 (a) to (e). It was found that the perforations began to lag behind the vibration wave, so that the vibration movement gained one cycle in about 45 000 revolutions. This verified the assumption deduced from the phase index data. In 45 000 revolutions, 45 001 vibrations occurred.

Although no such phenomena had been encountered on numerous spindles of this type, it was decided to replace this spindle by another of somewhat differ-

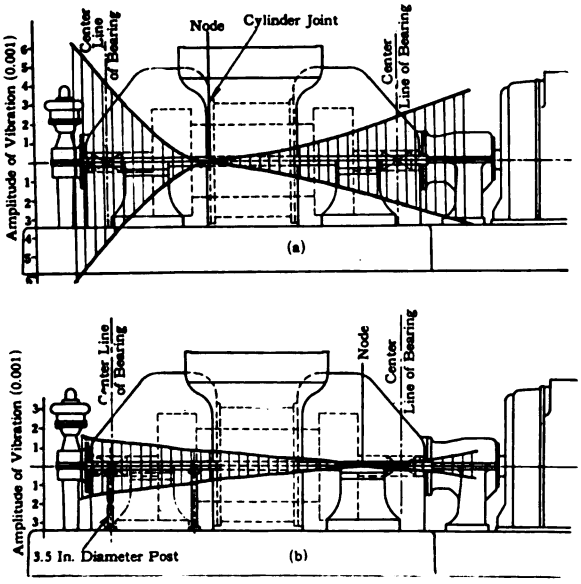


FIG. 11—SHIFT IN NODE AND REDUCTION OF VIBRATION BROUGHT ABOUT BY INCREASING FLEXIBILITY OF CYLINDER SUPPORTS TO AVOID RESONANCE

(a) Amplitude of vibration and location of node when turbine casing was supported on standard chairs.
(b) Amplitude of vibration and location of node when turbine casing at governor end was supported by posts.

ent construction, having greater bolt circle diameter, stronger bolts, and heavier body. In fact, the extreme was reached in the matter of rigidity and joint construction. The calculated critical speed in rigid bearings was naturally much higher. The new spindle was put through very severe tests in the shops, a special heating cylinder having been built with compartments permitting the heating or cooling of any section at will. Superheated steam at 650 degrees F. was used. The cylinder was arranged to enclose the spindle while in the dynamic balancing machine, so that the effect of the temperature changes could be determined at any instant with a high degree of accuracy. These tests proved this spindle also to be remarkably stable under all temperature conditions.

The new spindle was then installed, and it vibrated, if anything, worse than the original. The same cyclic phenomena developed, of somewhat shorter periods, but of greater amplitudes. Clearly the cause was external to the spindle. The spindle disturbance was of a secondary nature—a result and not a cause. A great deal of work was then carried out on the turbine cylinders, installing additional struts, stay bolts, etc., to secure greater rigidity. The result was nil.

About this time, C. R. Soderberg,* had been directing attention to the problem of vibration in elastic structures, with particular regard to resonance conditions and modes of vibration. Although the principles underlying resonance in its fundamental aspect had long been recognized, the general tendency had been to hold that, if the origin of the disturbance were eliminated, the vibration would take care of itself. Only resonance of structures in the simplest nodes had been considered; scarcely any practical study had been made

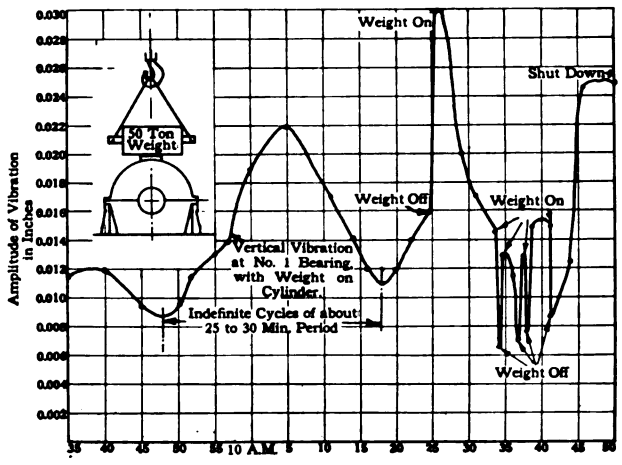


FIG. 12—EFFECT OF WEIGHT OF VIBRATION

Without weight, the cycles were sharply defined, with periods from 40 to 48 minutes.

of the more complex modes adopted by a structure for a particular forced frequency.

Investigations already made for possible foundation resonance on this installation had disclosed nothing of a definite nature. The foundation proper appeared to take but a small part in the vibration. A second investigation was now made, however, under the direction of W. B. Flanders, with especial attention to modes of vibration.

It had been observed that the maximum vibration occurred at the No. 1 bearing, and in the vertical direction, rapidly dissipating to relatively small amounts in the bedplate and foundation. When the amplitudes along the horizontal joint of the cylinder were explored, a node was disclosed near the joint between the middle cylinder and the thrust-end exhaust cylinder. The vibrating movement appeared to be in the nature of a rotation about this point. In Fig. 11 (a) the amplitudes are shown plotted along the horizontal joint.

*See THE ELECTRIC JOURNAL, January, 1924, for a series of articles on Vibration by Mr. Soderburg.

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Although no weakness as such was considered to occur at the joint, there appeared to exist an easy, natural mode of vibration about this point at the running frequency. When a complex elastic system is subjected to periodic forces at a certain frequency, the system selects modes of vibration to accommodate this particular frequency. At certain frequencies, easy modes occur due to the mass distribution, which require less energy to sustain vibration, and greater amplitudes result:—that is, a type of resonance is encountered.

To alter this condition, it was necessary only to change the mass involved, or the elastic scale. Adding considerable mass to the top of the thrust-end cylinder was tried with some result, but it was difficult to prevent the large mass used from vibrating about its own center of gravity, rather than force its center of gravity to take part in the vibratory movement. Thus the full advantage was not secured. In Fig. 12 are shown the amplitudes of vibration with and without the weight.

It is perhaps unnecessary to remark that the excessive vibration was not caused through any *fault* in the chairs—they were perfectly sound heavy iron castings—but by a rare chance combination of mass and elastic scale of both the rotating and stationary elements, in which the bedplate and foundation itself had their part as well. To the uninitiated it would appear that the turbine which vibrated excessively on the chairs would wreck itself when on the relatively slender posts.

It is of interest to note, however, that while the amplitudes of vibration were reduced to only a fraction of their former amounts, the sensitive vibrometers showed that the periodic phenomena still persisted. The periods of the cycles were considerably altered by the new supporting, being reduced to about 15 minutes. The peaks were of shorter duration, and occasionally were large enough to be conspicuous. Because of the long history of trouble with this unit, some concern was still felt over the persistence of the cyclic vibration,

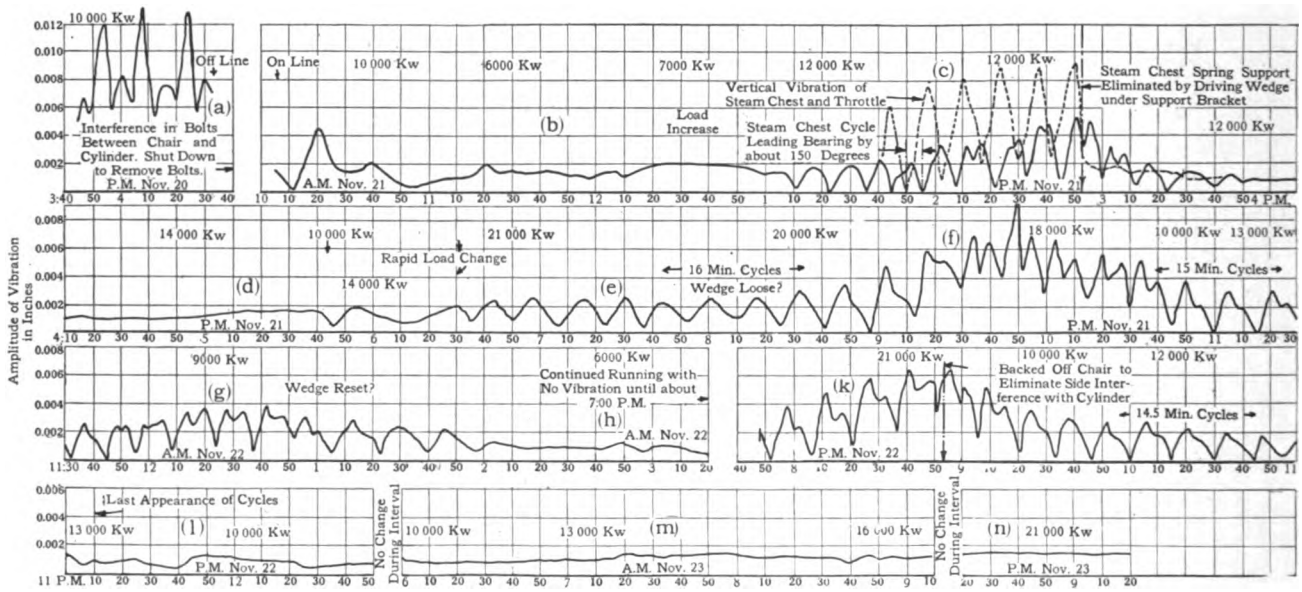


FIG. 13—RECORD OF VIBRATION WITH CYLINDER ON POSTS, SHOWING CHANGES IN CYCLES AND FINAL ELIMINATION

The amplitudes were reduced to some extent by the weight, but large fluctuations persisted. The amplitudes shown on this chart were usual for the new spindle, and were very severe.

To change the elastic scale of the system required the simple substitution of light flexible supports in place of the relatively stiff cylinder supporting chairs. This was accomplished by supporting the cylinder on slender posts of car axle stock, as shown in Fig. 11 (b). The loading deflection of the posts was several times greater than that of the chairs.

The effect was immediate and decisive. The amplitudes of vibration, which on the original chairs reached magnitudes greater than had been observed on any other similar turbine, were reduced at once to within passable limits. Fig. 11 (b) also shows the amplitudes along the horizontal center line with the new supports. It will be observed that the node has shifted back toward the coupling end.

however small. So long as the cycles existed, with their origin unknown, it was feared that the gradual growth of peak amplitudes which was encountered in the past might possibly reappear.

In effecting the final elimination of the cycles, several moves were made and features observed in such sequence that unfortunately there is some doubt as to the controlling factors. Naturally the academic aspect of the problem was submerged by the pressing necessity for accomplishing something to correct the trouble in the shortest possible time. It will be best perhaps, to recount the moves made and the observations in their chronological order.

In Fig. 13 is shown a fairly complete vibration record from the installation of the posts to the final runs which indicated the cycles were eliminated. The phase indicating apparatus was not available at this time. After the posts were installed the unit ran fairly well for a while, but gradually developed a cyclic varia-

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tion, the worst periods being shown at (a). The peaks have changed shape, being alternately large and small. At this time it was found that the chairs were not clear of the cylinder. The bolts through the top of the chairs to the cylinder were pulling up on the chairs. These were removed, a slight change in balance made, and the unit started up again.

After several hours of excellent running, on low loads, (b) the load was increased, and small cycles resulted, gradually increasing in amplitude. The peaks appeared to split into two parts as the amplitude increased. It was then noticed that the steam chest, throttle valve and main steam line, independently supported by springs at the side of the turbine, were vibrating at the maximum phase while the turbine proper was in the quiet phase. This relation is shown at (c). The steam chest cycle appeared to be leading the turbine cycle by about 150 degrees. It is believed that this feature also existed with the standard chairs, and also with the original spindle.

The steam chest and throttle as a unit were supported at the front and rear end by two springs carried in brackets attached to the bedplate. The greatest vibration was at the thrust end spring support. A wedge was driven at this point, eliminating the spring and carrying the load solidly on the bracket. The steam chest vibration was reduced at once, and the turbine cycles immediately decayed, disappeared in an hour, as shown on the record.

The unit ran perfectly for over two hours, as shown at (d). Cycles again commenced, the split peak feature developing first as a hip on the usual curve, as though two separate disturbances of slightly different periods were present. The peaks reached quite a maximum at (f), and then receded, the split peaks merging again into the usual single peak. A disturbance of lesser magnitude again developed (g), followed by about 18 hours of faultless running (h). Later, attendants reported that on several occasions the wedge at the steam chest support had worked loose and was reset, but unfortunately no record was made at the time. It is possible that the wedge was reset during the cycles shown at (g), although the constant low load maintained thereafter may have resulted in the long period of quiet running.

A large load change appeared to terminte the long quiet period, and cycles with hipped peaks again developed, shown at (k). It had been noted that the thrust end of the cylinder, freely supported on posts, travelled laterally through a range of about 0.030 in., the position depending on the load, moving toward the steam chest on the higher loads. It was now found that on the higher loads, this travel had been sufficient to cause an impactive interference on the chair on that side which had not been backed off sufficiently to clear. The chair was moved back to give ample side clearance, and the peaks at once diminished. After about two hours, the peaks permanently disappeared, as shown at (l), (m) and (n). These last records include instances when large load changes were imposed which always had started the cycles.

Shortly thereafter, the gland sealing water was accidently lost while the unit alone was carrying the entire system load. The frequency dropped to 40 cycles before the vacuum was re-established, but the turbine continued to run smoothly during this disturbance.

After about a year's running, the temporary wedge was replaced with a permanent support. It was reported that when the wedge was removed to effect this change, the small cyclic variations in vibration reappeared. During the two years which have elapsed, there has been no recurrence of the cyclic vibration with this exception, so far as is known.

This unusual vibration had resisted all efforts for nearly two years. A very great expense was incurred in revamping the original spindle and in supplying the new spindle, making cylinder alterations and in the continuous attempts at balancing during this period. There is every reason to believe that the original spindle as it was would have performed just as smoothly after the corrections with the cylinder post supports, and that there was no fault in either of the spindles.

The outstanding problem was the reduction of the excessive vibration. These great amplitudes were undoubtedly due to a type of resonance, and the major cure was effected by methods based on this assumption. The underlying cause of the freakish cyclic vibration remains for the present somewhat of a mystery. It was unfortunate that the exigency of the load situation did not permit the carrying out of an exhaustive investigation to learn the precise cause of the periodic disturbance. It is difficult to reproduce such phenomena by models. There have been occasional instances where the suggestion of a periodic vibration occurred, but these were of a transitory nature at most. No other cases of sustained periodic vibration have been encountered so far as is known.

The alternating vibration between the turbine and the steam chest suggested an abnormal energy-exchange phenomenon. Precession has been advanced as an explanation, but such a gyroscopic effect would require that both spindles have the same characteristics as regards perpendicularity of spindle end planes, press fits etc. The differences in the construction of the two spindles were too great to permit this. The split peaks observed with the operation on posts may be reproduced synthetically by two distinct rotating unbalances of different periods. This would suggest some connection with the fact that the spindle has two end sections. The secondary cycles may have been tied up with these features. Many installations have since been studied with the apparatus described, and on at least one occasion a single loop accompanying a sharp load change was found resembling the polar diagram figures, but there was no continuous rotation. The usual figures show a small indefinite migration within a confined area.

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# Electrical Insulating Oil

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DURING the past five years an increasing interest has been taken in insulating oil by public utility companies and other users of electrical apparatus. This has been partly due to the higher voltages used, making greater care necessary in the maintenance of the oil, but is also due to a better appreciation of the fact that, unless the oil is kept in thoroughly good condition, there is danger of failure of the apparatus in service.

In studying oil as an insulating medium for electrical apparatus it is desirable first to consider the various functions which it has to perform in different classes of apparatus. When used in transformers the oil provides an electrical insulating medium which carries the heat away from the windings. In circuit breaker service the oil is an insulating medium which will interrupt the arc when the circuit breaker operates.

### REQUIREMENTS FOR INSULATING OIL

In order to function satisfactorily the oil for either transformers or circuit breakers should have high dielectric strength. It should be free from inorganic acid, alkali and corrosive sulphur which might injure the insulation or conductors. Low viscosity is necessary in transformers to provide good heat transfer, and in circuit breakers it is especially important that the viscosity be low at all operating temperatures, to aid in dissipating the arc when the circuit is interrupted. Good resistance to emulsification is essential in circuit breaker oil, as this apparatus cannot be made airtight, and moisture is always likely to enter through breathing. The same quality which produces this characteristic also causes carbon formed by arcing to settle to the bottom of the tank. Resistance to emulsification is also desirable in transformers. In any oil-cooled equipment, water in suspension is a menace, as it not only lowers the dielectric strength of the oil, but also is deposited on the insulation, thereby lowering the surface insulation. Transformer oil should also be free from sludging under normal operating conditions.

It will be noted that the requirements for insulating oil for transformers are essentially similar, and in no case inconsistent with those for oil for service in circuit breakers. Thus, it is possible to standardize on a single grade of oil for all oil-insulated apparatus. There is a distinct advantage in the use of one grade of oil for all applications, both indoor and outdoor, thereby simplifying stocks, and reducing to a minimum the investment in oil, storage tanks, etc.

### MANUFACTURE

The production of electrical insulating oil involves the selection of a suitable crude oil, its distillation, treatment, testing and delivering to the customer in good condition. The properties desired are in some cases opposed to each other. For instance, in order to raise the flash point it is necessary to increase the viscosity. So the properties of the oil are a compromise.

One of the essential properties for outdoor circuit breaker use is a freezing point or pour test low enough that the oil will not be too viscous at the lowest temperature reached in service. The freezing point of mineral oil is determined by the crude from which it is derived. Some of the hydrocarbons present in mineral oil, especially paraffin wax, separate out at low temperatures. Hence, the lowest pour test obtainable with oil from paraffin base crude is about + 10 degrees F. Low pour test oil is made from napthene base crude, which contains little wax.

Distillation of the crude oil is carried on with the aid of vacuum to obtain a lower boiling temperature, thus avoiding decomposition of the oil, and the proper fractions for insulating oil are separated. The oil is then chemically treated to remove certain elements which would themselves deteriorate or cause the oil to deteriorate in time. This consists of agitating the oil with sulphuric acid, drawing off the acid and sludge formed, washing with water, neutralizing with alkali, and washing with water to remove the alkali. A thorough filtration through specially prepared fullers earth removes impurities and improves the color. The oil is then dried in a centrifuge or blotter filter press to insure the proper dielectric strength.

The greatest care is taken in handling insulating oil to avoid contamination. The containers are thoroughly washed and dried and given a careful internal inspection before filling. Both the container and the oil are warmed while being filled, to prevent condensation of moisture. Tank cars for insulating oil are usually lagged to minimize fluctuations in temperature of the oil during transit, with corresponding breathing which might result in condensation of moisture inside the tank. They are also usually provided with heating coils and are warmed while being filled with oil to avoid any possibility of condensation of moisture Dielectric tests are constantly being made on samples of oil taken from containers as they are being filled to make certain that the dielectric strength is being kept up to the required standard.

### STORAGE

*Storage Tanks* should be mounted clear of the earth so that they will be accessible at all points for inspection for leakage. A tank with a convex bottom is preferable, with a drain at the lowest point for removing

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any free water or dirt which may settle out. When a cylindrical tank is installed with its axis horizontal, one end should be a little lower than the other, with a drain at the lowest point, and the oil supply pipe should preferably enter at the opposite end of the tank. The oil may enter and leave the tank by the same pipe, but at some distance from the bottom to prevent stirring up any settlings when the tank is being filled. It is desirable to maintain the temperature of the oil and tank a little above the temperature of the surrounding air as this prevents condensation of moisture in the tank.

*Drums*—As soon as a drum of oil has been unloaded the bung should be examined and tightened if it is loose, as it is possible for bungs to become loosened by changes in temperature or rough handling in transit.

Drums should preferably be stored indoors. If it is necessary to store them outdoors, they should be elevated enough to protect them from ground moisture, and covered against direct rain or snow. They should be stored on their sides, with the bungs turned down at an angle of about 45 degrees. In any other position, and especially when stored on end, there is danger of moisture leaking in through defective joints.

Cans containing oil should not be exposed to the weather, nor opened until the oil is needed. It is not advisable to make dielectric tests on oil in the solder-sealed cans, as there is more danger of contaminating the oil in sampling for tests than of receiving oil of low dielectric strength.

*Refilling Drums*—It is not good practice to refill drums as, unless the greatest precautions are taken, the oil is likely to become contaminated. If it is necessary to refill them, drums which have contained only oil in good condition should be reserved for this purpose. Close them immediately after being emptied, to exclude dirt and water, and after refilling, examine them to see that they do not leak. When it is desired to use drums which have contained only good oil, but may have received some water, they should be drained, placed with the bung-hole down in an oven, and heated for sixteen hours at a temperature of at least 190 degrees F. The bungs should then be screwed on tightly before removing from the oven, using a new washer with the bung each time the drum is refilled, to insure a tight seal. Drums to be refilled for storage should be painted with a distinguishing color.

*Cleaning Drums*—It is preferable to return drums requiring cleaning to the refinery, where adequate facilities are available, rather than to attempt to clean them in the field. The preparation of clean drums requires great care. If it is necessary to clean drums which have contained used insulating oil, the following procedure is recommended:—

Rinse the drum thoroughly with gasoline or benzine, using about one gallon each time, until the solvent, after using, shows no discoloration. Allow it to drain, then pump out the last traces of solvent with a vacuum pump, using a brass pipe flattened at the lower end to explore the corners of the drum. (Steel should not be used because of the danger of a spark igniting the vapor.) Place the drum, with bung-hole down, in an oven heated to at least 88 degrees C. (190 degrees F.) for sixteen hours. Screw the bung on tightly before removing from the oven. Use a new washer with the bung to insure a tight seal. A simple oven for this purpose may be made from sheet metal and heated with steam or an electric heater. No open flame should be permitted near the oven.

### PLACING OIL IN SERVICE

The most careful precautions are necessary to insure that the apparatus is absolutely dry and clean before filling it with oil, and to prevent the entrance of water and dirt during the transfer of the oil.

*Cleaning Apparatus*—When putting a new circuit breaker or transformer into service, see that the tank is free from moisture and foreign material. When carbonized oil is removed from a circuit breaker in service, thoroughly clean the interior of the apparatus, so that the new oil will not be contaminated. This may be done by flushing with clean oil and wiping with clean, dry, lint-free, cotton cloths. Cotton waste is undesirable on account of the lint which may be introduced into the oil.

*Filling Apparatus*—It is preferable that the preparation and filling of outdoor apparatus be done on a clear dry day; if this is not practicable, suitable protection against water must be provided. Carefully inspect all vessels used for transferring the oil to see that they are absolutely dry and clean.

*Temperature*—Drums which have been outdoors should be allowed to stand in the room long enough to become warmed to room tempearture before breaking the seal. A drum of cold oil will sweat when taken into a warm room, and the moisture may mix with the oil as it flows from the drum.

*Straining*—Oil which has not been filtered should be strained through two or more thicknesses of muslin or other closely woven cotton cloth which has been washed and dried to remove the sizing. Replace the straining cloths as often as necessary. It is sometimes convenient to stretch the cloth across a large funnel.

*Hose*—Rubber hose is not suitable for handling oil, which can easily become contaminated from the sulphur in the rubber. Use metal hose.

*Testing*—Sample and test the oil for dielectric strength before transferring it to the apparatus. The oil in all apparatus should be sampled and tested for dielectric strength before the apparatus is put into service.

*Transferring Oil*—Oil which has been used in electrolytic lightning arresters cannot be used in transformers or circuit breakers, as it contains harmful impurities which cannot be removed in the field.

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MAINTENANCE

*Causes of Deterioration in Transformers*—The principal causes for the deterioration of oil in service are water and oxidation. The oil may be exposed to moisture through condensation, due to breathing of the transformer, especially when it is in service intermittently. Water may also enter from leaky cooling coils or a leaky cover.

Sludge is an oxidation product, the amount formed being dependent upon the temperature and the time of exposure to the air. Oxidation is carried on not only on the surface, but also to some extent throughout the oil due to dissolved oxygen. Light, heat and some materials used in transformers accelerate the oxidation. By careful refining, the components of oil which form sludge most readily can be removed, so that the oil will not sludge under normal operating conditions. Excessive temperatures may cause sludging of any transformer oil, regardless of how well it is refined.

Oil which has begun to sludge will continue to do so after it has been purified by means of the centrifuge or filter press, as these methods of purification do not remove the deterioration products which are in process of formation but have not yet been thrown down as sludge. No method is yet available in the field which will remove these products, bringing sludged oil back to its original condition. It is usually not economical to return used oil to the refinery, as only a small price is allowed for it.

Oxygen also gradually produces organic acids in oil. These should not be confused with the mineral acids used in refining. In small amounts they do not have a deteriorating effect upon insulation. There is no adequate method available in the field for purifying oil of high organic acidity.

In an effort to produce oil which has the lowest possible tendency to sludge, it is possible to over-refine it. Such an oil develops organic acidity, which increases rapidly to a point where it becomes a menace to insulation. This high acid development is characteristic of some of the so-called water-white oils.

There is at present no adequate method for determining the sludging tendency of oil. A number of accelerated tests for oxidation and acid-forming properties have been suggested and are being studied by the American Society for Testing Materials. None of them duplicate conditions in transformer service. Obviously any method to be of value must be correlated with data on the oil in actual transformer service.

*Causes of Deterioration in Circuit Breakers*—The principal causes of deterioration in circuit breakers are water and carbonization caused by opening the arc. Water may enter by condensation or by leakage.

Some carbonization takes place whenever the circuit is interrupted, even on light service. The resistance to emulsion of the oil is also lessened, both by a change in the oil and by the presence of carbon in the oil. The carbon lowers the dielectric strength of the oil and the surface resistance of the insulation if water is present, and also lowers the resistance to emulsification or the property of separating out any water present. The carbon may not be detected by the dielectric test, particularly if the oil is free from moisture.

INSPECTION AND TESTING

To maintain the oil in proper condition, it is essential that periodic inspections and tests be made. The frequency of inspection and testing depends upon the service to which the apparatus is subjected. A definite schedule should be followed, based upon the operating conditions, taking into consideration the dielectric test reports on the oil. The interval between successive inspections should never be longer than six months.

When the dielectric strength of the oil drops to 20 kv in the standard dielectric test, the oil should be closely watched, and in no case should it be allowed to drop below 18 kv.

Inspection of oil in service should include a check on the following:—

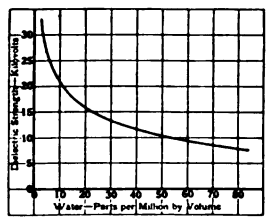


FIG. I—EFFECT OF WATER ON OIL

*Oil Level*—It is essential that the proper oil level be maintained. Low level may cause a breakdown of insulation or flashover at bushings, or failure of a circuit breaker to open overloads.

*Dielectric Strength* — The oil should be tested regularly for dielectric strength, and purified promptly when necessary. It is particularly important to check the dielectric strength in a circuit breaker after opening a severe overload.

*Carbonization*—The presence of carbon in circuit breaker oil introduces a hazard due to the tendency of the carbon to lower the dielectric strength of the oil, particularly in the presence of water, and also to deposit on insulating surfaces, reducing the insulation resistance. Visual inspection of the oil samples should be made and the oil purified if any appreciable amount of carbon is present, even though the dielectric strength is good.

*Sludge*—Transformers should be regularly examined for evidence of sludge. Appreciable amounts of sludge may clog the oil ducts or deposit on the windings and interfere with heat transfer. Such oil should be purified immediately, and when put in service again it should be carefully watched to maintain the proper dielectric strength, and to purify the oil again before sludge has formed once more to such an extent as to interfere with operation. Oil which has once sludged will sludge more quickly after being purified than the first time.

*Resistance to Emulsification*—The test for resistance to emulsification gives a good indication of the ability of the oil to throw down moisture and also to

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precipitate carbon developed by arcing in a circuit breaker. This property of an oil is impaired by the opening of a circuit breaker. Good resistance to emulsification is essential for both transformer and circuit breaker applications. There is always a possibility of water entering the oil and in such an event it is dangerous to have the oil in such condition that it will hold the water in suspension, with consequent lowering of the dielectric strength.

### SAMPLING OIL FROM SHIPPING CONTAINERS

As nearly all samples of oil are tested for dielectric strength, the comments on sampling are made with particular reference to this test. The extreme influence of even minute traces of certain impurities, especially water, on the dielectric strength, is not fully appreciated by most operators. The greatest care must be used in taking the samples and in handling them to avoid contamination. Wet or dirty sample containers or sampling tubes may have a considerable effect on the test results obtained. Many cases where low dielectric test results have been reported from the field have been caused by carelessness in sampling. The procedure described below, based on the recommendations of the American Society for Testing Materials, should be closely followed in order to secure accurate results.

*Sample Bottle*—The sample container should be of at least eight ounce capacity. A clear glass bottle is preferable to a metal container, as it may be examined to see if it is clean, and allows visual inspection of the oil before testing, particularly as regards free water and solid impurities. If a sample is to be tested for color or sludge-forming characteristics, it must be kept in the dark, as light produces changes in these properties. Use a new, high quality cork for each sample. Before using, the sample bottle should be thoroughly cleaned with benzine or gasoline which has previously withstood a dielectric test of at least 25 kv, and allowed to drain. Unless it is to be used immediately, the bottle should be tightly corked and the cork and neck of the bottle dipped in melted paraffine. Rubber stoppers should not be used as the sulphur in the rubber will contaminate the oil. It is preferable to heat the bottle and cork to a temperature of 210 degrees F. for one hour after thoroughly draining, and cork the bottle while hot.

*Thiefs for Sampling*—Samples are taken by means of so-called thiefs, which are especially adapted to obtain the desired sample from any part of the drum or apparatus with the minimum possibility of contamination. A convenient and simple thief may be made as shown in Fig. 2. In an emergency a piece of glass tubing, 36 in. long, may be used. For the tank cars, a thief employing a trap at the bottom as shown in Fig. 3, may be used.

Before using, the thiefs should be cleaned by rinsing with dry gasoline, taking special care that no lint or fibrous material remains on them. When not in use they should be kept in a hot, dry cabinet or compartment, at a temperature of not less than 38 degrees C. (100 degrees F.) and should be stored vertically in a rack having a suitable drainage receptacle at the base.

*Procedure*—Samples should not be taken outdoors if any other arrangement is possible. If the containers have recently been brought indoors, sampling should not be done until the oil is at least as warm as the surrounding air, as otherwise enough moisture may condense on the surface from humid atmosphere to affect the insulating properties.

The method of using a thief is to close the top with the thumb, quickly thrust the thief to the lower part of the container and remove the thumb. When the thief is filled the thumb is replaced, the thief quickly redrawn and the contents allowed to flow into the sampling receptacle. The sample should be taken with the thief about 1/8 in. from the bottom of the container. Neither the oil nor the lower part of the thief should be touched during this operation.

When the sample receptacle is filled it should be closed quickly and the bung replaced in the container and tightened. The sampling receptacle should be taken under cover to the testing laboratory as quickly as possible.

A tank car of oil should be sampled by introducing the thief through the manhole on top of the car, cover of which should be removed carefully, so as not to contaminate the oil. This should not be done while rain or snow is falling, or even during a heavy fog. The sample should be taken from near the bottom of the tank.

*Sample*—It is recommended that one pint of oil be taken as a sample for dielectric tests, and one quart sample be taken when complete physical and chemical tests are to be made. At least one sample should be taken from a tank car of oil. One sample may be taken from each drum or, if desired, a composite sample may be made from oil from five drums, provided all of the drums are air tight. When first loosening the bung, a hissing sound should be heard, indicating that the drum has been air tight. If the test of the composite sample is not satisfactory, a sample from each of the drums represented should be tested. When drums are stored exposed to the weather, a sample from each drum should be tested.

The sample of oil should be examined visually for free water, and if any is noted the sample and bottle should be discarded, as a dielectric test is not necessary to show low dielectric strength. This statement might seem to be superfluous, but cases are known where the tester carefully shook the water and oil in the bottle so as to disperse the water through the oil and get an average dielectric test. If the sample from a tank car is discarded on account of water being present, sufficient oil should be drawn from the bottom of the tank to remove all free water before obtaining another sample for the dielectric test.

### SAMPLING OIL FROM APPARATUS

When taking samples of oil from a circuit breaker or transformer where a thief cannot be used, the procedure outlined above should be followed as far as practicable. In addition, care should be taken to procure a sample which fairly represents the oil at the bottom of the tank. Such equipment usually contains a sampling pipe and valve for this purpose. Sufficient oil should be drawn off before the sample is taken to insure that the sample oil will not include any that was stored in the sampling pipe. For this reason the valve and the drain pipe should be sufficiently small to be emptied with convenience and yet large enough to avoid clogging by sediment. A ¼ in. pipe and valve is recommended. This, of course, may be separate from the drainage pipe and valve or may be connected to the drainage valve by means of a suitable reducer.

When the apparatus is installed outdoors care should be taken to prevent contamination of the sample by rain, snow, etc.

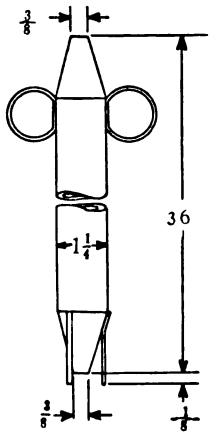


FIG. 2—A DRUM THIEF FOR SAMPLING OIL

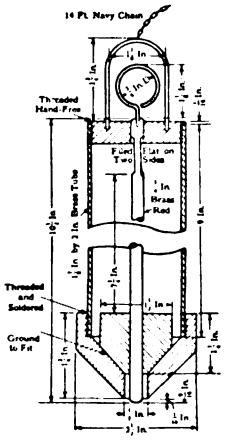


FIG. 3—A TANK CAR THIEF FOR SAMPLING OIL

*(To be Continued)*

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# High-Slip Versus High-Torque Motors

## Their Application and Characteristics

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IT has long been known that an increase in the rotor resistance of an induction motor, without changing other design constants, results in an increase in slip and, up to a certain point, increased starting torque, without change in maximum or pull-out torque. Hence there is a widespread idea that the terms "high-slip" and "high starting torque" are synonymous. This is not necessarily the case. Two motors of the same rated horse-power and speed may be designed to vary widely in reactance and other characteristics, depending on the purpose for which they are intended. Hence a high-slip motor may have a fairly low starting torque; and a motor with high starting and pull-out torques may have a low slip. These points will be discussed with reference to the speed-torque curves of three typical motors, which represent probably the most common variations from what might be considered a "normal" motor:—

*A*—A high-slip motor, designed with a high-resistance rotor and normal reactance.

*B*—A high-torque motor, designed with a normal rotor resistance and low reactance.

*C*—A motor designed with a high-resistance, low-reactance starting winding and a low-resistance, high-reactance running winding, such as a motor with a double squirrel-cage rotor winding, the starting winding being near the rotor surface or air-gap and the running winding deep in the rotor core below the starting winding. The load current is shifted automatically from the starting winding to the running winding by the change in rotor reactance as the rotor speed increases.

Only the speed-torque and current characteristics of these motors will be discussed. In general, however, the value of the current for the full-load torque of the motor will serve as a measure of the power-factor and efficiency at full load. The product of the power-factor and efficiency gives the apparent efficiency of the motor. From this it is seen that the motor having the lowest value of current will have the best apparent efficiency.

Referring to Fig. 1, for simplicity the three motors are assumed to have the same value of full-load torque. This is not strictly true, since for a given horse-power output the torque of the lower speed or high-slip motor must be more than for the two other lower slip motors, horse-power output being proportional to the product of torque and speed[1]. However, this assumption of equal torques for the three motors will introduce only a slight error which is negligible for this discussion.

Because of the confusion of terms, in some cases, high-torque motors have been applied where high-slip motors should have been used. A high-slip motor should be used on such applications as shears, punch presses and all flywheel applications where the motor must slow down to allow the flywheel to give up its kinetic energy, with sufficient time between the operations of the machine to allow the flywheel to gain speed and store up sufficient energy for the next operation.

[1] *Horse-power = (torque × r.p.m.)/5250.*

In Fig. 1, $A_1$ is the speed-torque curve and $A$ is the current-torque curve for a high-slip motor. This is the proper motor to use for a flywheel application. Assume that the normal speed is 870 r.p.m.; and that a load is instantly applied which requires the flywheel to slow down to 750 r.p.m. to give up sufficient kinetic energy to do the required work. The term normal refers to the speed or current when the motor is driving the machine, but the machine is not shearing or pressing metal. From curve $A$ the current at 870 r.p.m. is 13 amperes, while at 750 r.p.m. it is 47 amperes. From this it is seen that when such a load is applied to this motor the current increases to 360 percent of its normal value. Suppose a low-slip motor, as shown by speed-torque curve $B_1$ and current curve $B$, is applied to the same flywheel application. The normal speed at the assumed torque will be approximately 885 r.p.m. Neglecting the slightly higher value of kinetic energy of

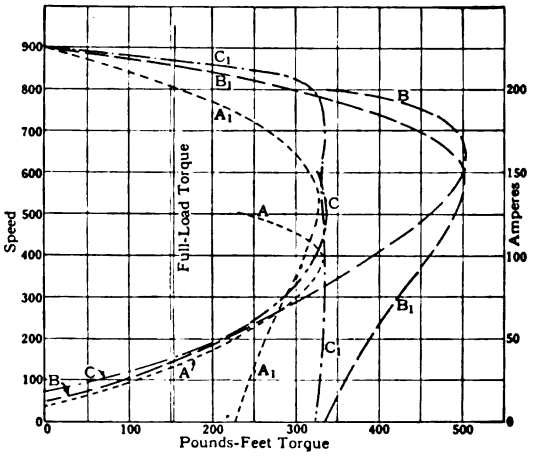


FIG. 1—SPEED-TORQUE AND CURRENT CURVES OF 25 H-P, 8 POLE, 60 CYCLE INDUCTION MOTORS

$A_1$ = Speed-torque curve of a high-slip motor.
$B_1$ = Speed-torque curve of a high-torque motor.
$C_1$ = Speed-torque curve of a line-start motor.
$A$ = Current-torque curve of a high-slip motor.
$B$ = Current-torque curve of a high-torque motor.
$C$ = Current-torque curve of a line-start motor.

the flywheel due to its slightly higher speed, and assuming its drop in speed will be the same as for the high-slip motor, in order to give up its stored energy, results in a speed of 765 r.p.m. From the current curve $B$ the value is 18 amperes at the normal speed and 88 amperes at 765 r.p.m. This means that every time the load is applied, the current increases to 488 percent of its normal value.

A graphical comparison of these two motors on flywheel application is given in Fig. 2. The ascending part of each peak represents the increase of current as the flywheel slows down in providing sufficient energy to do the required work. The descending slope represents the restoring of normal speed to the flywheel. The constant low value of current is the normal cur-

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rent at normal speed. The peak current values of the two motors are displaced for clearness only. From this comparison, the reduction in peak current obtained by a high-slip motor and the effects of a low-slip motor in regard to fluctuating line current and excessive heating due to the high value of current, are evident when placed on a flywheel application. The same reasoning can be applied to the motor shown in Fig. 1 by current curve $C$ and speed-torque curve $C_1$. This motor will also have the same or similar effects as the low-slip, high-torque motor just discussed.

Motors for flywheel application seldom require a high starting torque, the standard torque value being sufficient. For such application, the motor should be referred to as a high-slip motor and not as a high starting torque motor.

On the assumption that a high-slip, high-resistance rotor motor is a high starting torque motor, high-slip motors have been used for applications such as conveyors, compressors, etc. On these applications a low-slip, high starting torque motor should be used, as the motor must start a heavy load from rest and the running speed should be as high as possible. A difference in speed on a conveyor or similar application of 100 r.p.m. may slow up the handling of material, etc., considerably; also the speed variation of the motor from no load to full load should be practically constant.

If a high-slip motor such as motor $A$ were applied to a conveyor or similar application, it would be necessary to use a larger motor. As seen from Fig. 1, curve $A_1$, the torque at start would not be sufficient, assuming the torque required were 200 percent of full load. This value of torque is usually the minimum allowable for conveyor and similar applications. A larger motor means greater cost and, since most motors operate at their maximum efficiency near full load, the operating cost may be increased slightly.

From this discussion and the curves shown in Fig. 1, it is evident that a motor designed for flywheel applications should not be used on applications where high starting torque and high full-load speed are required.

The torque curves shown in Fig. 1 are good examples of ideal torque curves. These three torque curves are free from cusps, and the three motors are capable of bringing up to speed any load they can start. The shape of the torque curve is of importance, as a cusp in the curve which reduces the torque between start and maximum points to a value considerably below the starting value may result in the motor failing to come up to speed. This would require replacement of the motor with one which has a torque curve approaching the curves in Fig. 1, or a motor of higher rating.

It is usually recommended that a motor have nearly 200 percent of full-load torque at its maximum or pull-out point. For most applications this is not necessary. Comparing the maximum torque value of the motors shown in Fig. 1, the line-start motor and the high-slip motor have approximately the same value of maximum torque, namely, 213 percent of full-load torque, whereas the high-torque motor has 325 percent of full-load torque at its pull-out point. The horse-power of these motors at their maximum or pull-out points are 34.6 for the high-slip, 48 for the line-start and 57.7 for the high-torque motor. Obviously the value of maximum torque in terms of full-load torque is not always a measure of the maximum horse-power that a motor will deliver momentarily without overheating or pulling out.

The starting currents of the three motors under discussion can be taken from the current curves in Fig. 1. They are the extreme upper ends of the curves. There is not much difference between the starting current for the high-slip and the line-start motor, but the high-torque motor takes considerably more current at start. The value of pounds-feet torque at start per ampere of current at start is found to be 21.6 for the line-start motor, 17.4 for the high-slip motor and 16.7, for the high-torque motor.

High starting current is objectionable on some electrical systems where starting the motors draws sufficient current to cause a disturbance on the line. The value of starting current for the high-torque motor can be made equal to the starting current for the line-start motor by a reduction in maximum torque to the line-start value, but the starting torque will also be reduced in approximately the same ratio as the reduction in maximum torque. Therefore, the motor would no longer be a high starting torque motor. From this is seen that the line-start motor would be the logical one to use on a high starting torque application, since it has a starting torque equal to the high-torque motor, and a much lower starting current. The fact that the maximum horse-power and torque are less than for the high-torque motor is not of importance, as it has sufficient maximum horse-power and torque for almost any application.

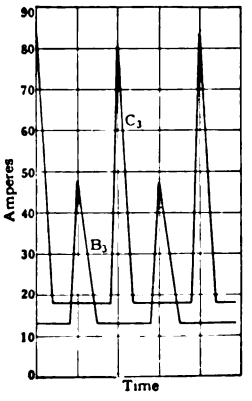

FIG. 2—FLYWHEEL APPLICATIONS

From the foregoing discussion and the speed-torque and current-torque curves in Fig. 1, the following conclusions can be drawn:—

a—A high-slip motor is not necessarily a high starting torque motor, i.e., a motor with a high rotor resistance does not always have high starting torque.

b—A high starting torque motor can be built without a high-resistance rotor, in which case it is not a high-slip motor.

c—Two motors of different design can have the same starting torques and different pull-out torques; or they can have the same pull-out torque values and different starting torque values.

d—Two motors of different design can have widely different values of starting current for the same starting torque; or they can have different values of starting torque for the same starting current.

It is seen, therefore, that in specifying a motor for a given application it is better to do so, not on the basis of design characteristics, but on the basis of operating characteristcs desired.

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# Oscillography

## IX-Polyphase Galvanometer Control for the Multi-Element Oscillograph

JOSEPH W. LEGG

NOT many years ago the oscillograph was considered to be laboratory apparatus requiring a highly trained operator. The modern oscillograph is being used in many power stations and is even operating automatically to record instantaneous power, average power and power-factor, as well as instantaneous potential and current. Even though old outfits were very limited in their application they were complex and bothersome in their operation. The modern instrument can solve the most complex problems in the most simple way. For two years oscillographs have been operating automatically in the Southern California Edison System with only occasional attention from station attendants. These outfits have been improved and simplified so that they may be set up for automatic operation without the help of a specialist. Furthermore standard outfits will record polyphase power, positive or negative phase-sequence voltage, instantaneous watts, power-factor, and instantaneous values of ground current, line currents, line potentials, etc.

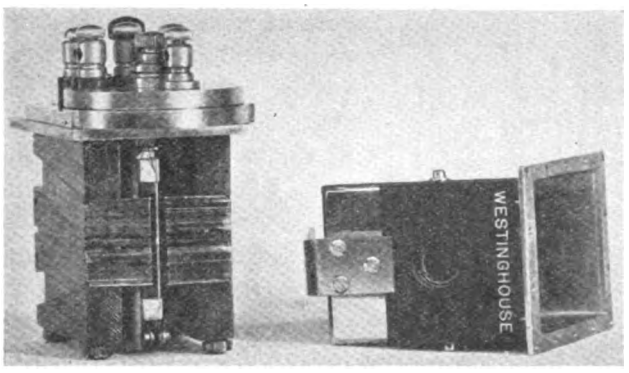


FIG. 1—A FRONT VIEW OF THE POLYPHASE INSTANTANEOUS WATTMETER

Showing the case and the vibrator assembled in the double field.

The importance of protection, stability and continuity of service in high-power lines is becoming so apparent that enterprising operating engineers welcome the opportunity for utilizing instruments which will tell the whole story in a reliable way.

The fact that an instantaneous single-phase wattmeter could be made small enough to be interchangeable with the smallest permanent-magnet galvanometer seemed remarkable enough, but now there is a polyphase instantaneous wattmeter just as small as its single-phase predecessor. These interchangeable units are but 1.5 in. wide and 3 in. high from the bottom of the oil chamber to the top of the vibrator terminals.

### POLYPHASE INSTANTANEOUS WATTMETER

Two views of the disassembled parts of the polyphase instantaneous wattmeter are shown in Figs. 1 and 2. This instrument will record the total watts of a three-wire system no matter how unbalanced is the load. By Blondel's theorem a wattmeter may have one less moving coil than there are wires in the power line and yet record total power even under unbalanced conditions. Fig. 1 shows the double vibrator in place between the double set of pole tips of the laminated-core magnets. The two sets of laminations converge as they approach the front. The tiny vibrator mirror is in the center between the four poles of the magnets. Actually there are but two vibrator strips, which run from terminals at the top of the vibrator stem to the levers at the bottom of the stem. Beneath the mirror, the strips are joined by a cross piece of the same material. Four terminals are supplied, the front and rear going to the top of the strips, and thus serving the upper coil; and

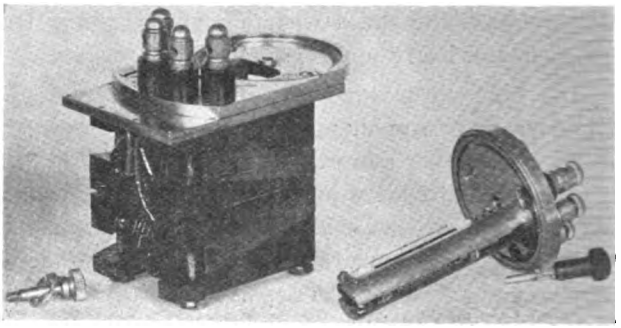

FIG. 2—A REAR VIEW OF THE POLYPHASE INSTANTANEOUS WATTMETER

Showing the two current coils and four terminals. The rear of the double vibrator is shown at the left.

the other two terminals (one at each side of the rear terminal) passing down flexible leads to the two insulated levers and thus serving the lower coil. Because these two coils have a common electrical point, under the mirror, it is necessary to feed them from secondaries of insulating transformers, as shown in Fig. 3. The oil-tight case with its lens window is shown at the right in Fig. 1.

In Fig. 2 the rear of the magnets with the two five-ampere coils are shown. These coils are fed from series transformers so as to excite their relative magnets in proportion to the instantaneous values of current in the power lines. The four terminals, for the two current coils, are shown on the top plate of the galvanometer proper. The double-coil vibrator unit is shown at the right. The helical spring in the rear cavity of the stem can be seen in this view. Equal tension is transmitted to each vibrator strip through a pulley, a fine cord and the two levers at the bottom of the stem.

The natural period of vibration, without oil, is

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approximately 2500 cycles per second. The currents in the potential coils (vibrator) range from 0.04 to 0.15 ampere according to the conditions to be met. Each potential coil has a resistance of less than one ohm, and is strictly non-inductive. Hence the consumption of each potential coil is usually less than one hundredth of a watt. Less than five volt-amperes are taken by each current coil at full load with 60 cycles supply. At this full-load value the coils consume approximately 1.5 watts apiece, but at usual continuous loads the consumption is but a small fraction of this.

Since these instantaneous polyphase wattmeters are used mostly to show conditions during great overloads or short-circuits on the power system, the continuous

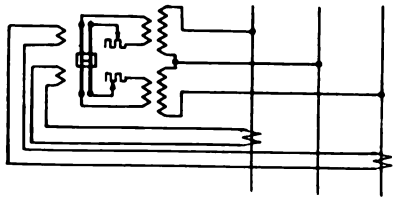

FIG. 3—CONNECTIONS FOR DOUBLE COIL WATTMETER

current in the wattmeter is usually one-fifth or one-tenth the test value, so that the wattmeter current coils usually operate at a continuous total loss of but one-tenth watt or less. If each current winding in the wattmeter is designed for five amperes full load, then external current transformers must be used to reduce the high secondary currents (of possibly 25 or even 50 amperes) of the standard current transformers, to an amount not exceeding eight amperes in the wattmeter. If the wattmeter current exceeds eight amperes, saturation of the iron begins to make the record digress from a uniform straight-line calibration.

If one of these instantaneous wattmeters is to be used in a certain power system where the transient currents are always nearer 30 amperes than five amperes, then the cores may be wound with approximately one-sixth as many turns of larger wire so that no additional current transformers would be required. Even in such a case, the continuous current would not exceed four amperes, even though the momentary peak of current might be 50 amperes. The multi-element oscillograph is provided with holes in the upper part of the back of the micarta case so that current leads may enter to pass on to the watt galvanometers. These holes are normally closed by threaded plugs which may easily be removed whenever it is desired to introduce the current leads.

### POTENTIAL TRANSFORMERS

A twin-transformer arrangement has been developed for power-recording applications. This pair of transformers (or the equivalent) must be used with the polyphase instantaneous wattmeter, because of the double-coil vibrator having a common point, under the tiny mirror. The twin-transformer panel[1], developed for the Power Osiso, is shown in Fig. 4. This may be supplied in an attractive case for use external to any

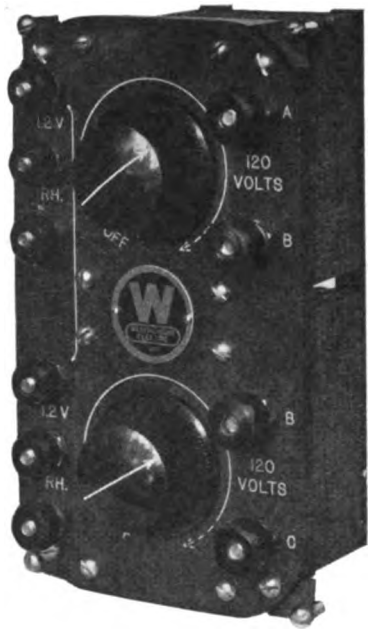


FIG. 4—THE TWIN-TRANSFORMER PANEL FOR INSTANTANEOUS WATTMETER

Osiso or multi-element oscillograph. However, when this unit is used with the polyphase instantaneous wattmeter it cannot be used to supply a positive-phase-sequence voltage element, at the same time.

### HALF-LENGTH PANELS

A more flexible twin-transformer panel has been designed for the multi-element oscillograph. One of these panels occupies one-quarter of the space beneath the galvanometer compartment and affords control for all potential circuits to give the following:—Positive (or negative) phase-sequence volts; also polyphase instantaneous watts, or, in place of the latter, single-phase instantaneous watts and line-to-line or line-to-neutral volts. The arrangement of this half-length panel is shown at the right in Fig. 5. This panel contains a reactor and two potential transformers, each of which has two secondaries. One secondary of each transformer is used for the positive phase-sequence voltage

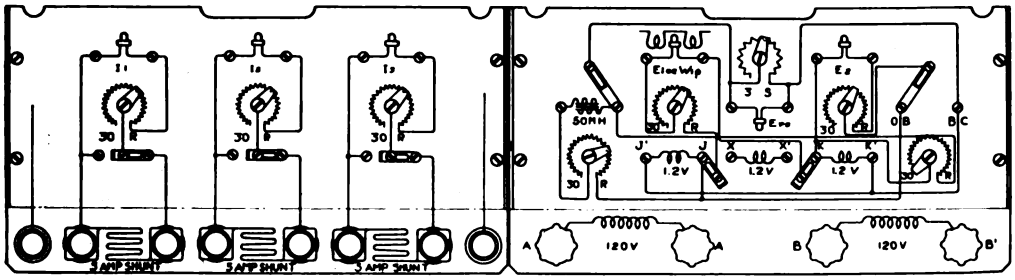


FIG. 5—THE HALF-LENGTH POTENTIAL-CONTROL PANEL AND CURRENT CONTROL PANEL

[1]See the JOURNAL for Oct., 1927, p. 511; Dec., 1927, p. 620.

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network, while the other secondary may be used for the polyphase instantaneous wattmeter. Uusually the two 120-volt primary windings are connected together at $A'$ and $B$ so that $A$ goes to line $A$, $B$ to line $B$, and $B'$ to line $C$. Five adjustable resistors and four adjustable links are supplied on the vertical face of the unit.

The upper left-hand link controls positive or negative phase sequence. The two lower resistors are in this phase-sequence network to obtain the proper resistances to go with the 50 mh. reactor. For 60-cycle supply the resistor (left) in series with the reactor should be set to give a total of 11 ohms while the other (right) should be set at 22 ohms, the reactance being 19 ohms (or 86.6 percent of 22 ohms). The upper resistor (3 ohms) is used in shunt with the vibrator element to adjust the deflection of phase-sequence volts.

When the links are set as in the illustration (right-hand part) the upper right-hand vibrator is recording the potential from line $B$ to neutral ($BO$). If the right-hand upper link is shifted to the right then this vibrator will record the voltage from line $B$ to line $C$. The upper left-hand vibrator is connected to record single-phase instantaneous watts[2] (potential $BO$) from which record may be scaled power-factor, average power, and reactive power (or kv-a). Now if the two lower links are shifted from $J$ and $K$ to $X$ and $X'$, and if the right-hand upper link is shifted to $BC$, the polyphase instantaneous wattmeter may have its double-coil vibrator fed from $E_1$ and $E_2$ while its current coils receive currents proportional to those in line $A$ and line $C$.

The left-hand unit of Fig. 5 has three adjustable resistors and three 5-ampere current shunts. This furnishes a simple control for three simultaneous current records. A total of four of these units may be used in any multi-element oscillograph. With one current-control unit and one potential-control unit it would be possible to show: single-phase instantaneous watts; negative phase-sequence volts; volts from $B$ to $O$; current in neutral (ground current); current in line $B$, and direct current in the field circuit of the alternator. In the latter case the link above the 5-ampere shunt should be placed in neutral position, and a pair of leads extended from the left-hand terminal and the link to a suitable current shunt in the field circuit.

Two three-phase lines can be studied with one oscillograph if two potential-control units and one current-control unit are used. Polyphase watts in each delta system could be obtained as well as positive and negative phase-sequence volts and three total currents. In some cases it may be desirable to have three of the potential-control units and but one current-control unit in one oscillograph. With the nine-element outfit this would make it possible to show polyphase watts in three different delta systems and to show positive and negative phase-sequence volts in at least one system, besides a potential from line to ground or line to line and also three currents, including at least one ground current.

### FULL LENGTH PANEL FOR POTENTIAL CONTROL

A much more complete potential-control panel for showing all desirable features of one system is shown in Fig. 6. This panel is full length and takes up half of the space below the galvanometer compartment. This

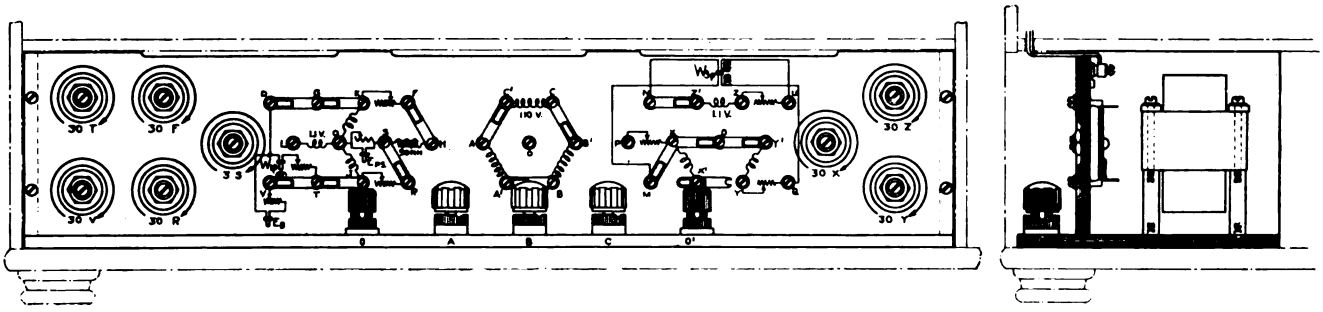


FIG. 6—THE FULL-LENGTH POTENTIAL-CONTROL PANEL

unit includes a reactor and three potential transformers. Each potential transformer has two secondaries. Fourteen links and thirty studs make it possible to vary the potential connections to the various vibrators of the oscillograph. The primaries may be connected in star or in delta. The primary windings are $AA'$, $BB'$, $CC'$. The secondary windings are $XX'$, $YY'$, $ZZ'$ and $JJ'$, $KK'$, $LL'$ respectively. When three-phase (50 to 70 cycles) 110 volts is connected to terminals $ABC$ the secondary potentials are 1.1 volts each. The right-hand set supplies the polyphase wattmeter. The arrangement of links as shown is for three-wire lines to record polyphase instantaneous watts. The links may be shifted symmetrically about $O$ to supply a polyphase average-value wattmeter having three moving potential coils and three stationary current coils. The three adjustable resistors at the right are for controlling the potential circuits of polyphase wattmeters. The resistor from $P$ to $X$ is inactive as shown, but must be used with the average-value wattmeter, which records total watts in a four-wire system (three-phase with grounded neutral).

The set of secondary windings to the left control the positive (or negative) phase-sequence voltmeter $E_{PS}$, the single-phase instantaneous wattmeter $W_{1P}$ and the potential vibrator $E_B$. The five adjustable resistors to the left are shown diagramatically in the circuits about the links and studs. The engraving 30$T$ implies 30 ohms in circuit T, for $W_{1P}$. Likewise 3$S$ implies 3 ohms in circuit $S$ in shunt with $E_{PS}$. Now 30$F$ and 30$R$,

[2]See the JOURNAL for Dec. 1927, p. 619, Fig. 6.

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together with the 50 millihenry choke from $S$ to $H$, control the adjustment to give positive (or negative) phase-sequence volts on $E_{PS}$. $R$ is adjusted for 22 ohms and $F$ for 11 ohms total, for 60 cycles (or 18.2 and 9.1 ohms for 50 cycles).

The reactance of the choke must equal 86.6 percent (sin 60 degrees) of the resistance of the non-inductive circuit, and the total resistance of the reactive circuit must be half (cos 60 degrees) of that of the non-inductive circuit. When the line is balanced, and these settings are made correctly, then the vibrator $E_{PS}$ shows no deflection when connected for negative phase-sequence volts. When lines $A$ and $C$ are reversed then $E_{PS}$ records positive phase-sequence volts, and thus shows a reduction in deflection when any one line potential drops, or when all three phases drop. The same effect can be obtained by shifting the link from one side of the choke to the other and by interchanging the values of resistance in $R$ and $F$ (instead of reversing lines $A$ and $C$.)

With all links as shown, the current in the single-phase wattmeter ($W_{1P}$) must be that in line $B$. If the link is shifted from $TJ$ to $TL$ then the current in line $C$ must be chosen for $W_{1P}$. On the other hand, if the link is shifted from $DK$ to $DL$ the current in line $A$ should be chosen.

If the polyphase wattmeter is not used, then the right-hand set of secondaries and resistors may be used to supply three voltage vibrators, to give three line-to-line voltages or three line-to-neutral voltages.

By using two of these full-length potential-control panels, in one nine-element oscillograph, it is possible to study two generating systems at once by recording the following values in each; polyphase watts, phase-sequence volts, single-phase instantaneous watts (from which may be deduced power-factor and reactive power) and one current (in line or in neutral). One vibrator element then remains for a constant-time marker. Thus it is seen that these resistors, studs and links, make a very flexible arrangement for the control of the potential circuits of galvanometer vibrators.

### CURRENT TRANSFORMERS

When the links are all set as shown in Fig. 6, there should be current transformers in lines $A$ and $B$ in order to feed the polyphase instantaneous wattmeter, at the right, and the single-phase instantaneous wattmeter, at the left. The $ZZ'$ secondary feeds the upper potential vibrator through $U$ and $N$, and the upper current coil is fed by the current transformer in line $A$ The $YY'$ secondary feeds the lower potential vibrator through $Q$ and $M$, and the lower current coil is fed by the current transformer in line $B$. This same current transformer feeds the current coil of the single-phase wattmeter. Since the links may be varied to suit almost any requirement, it should be understood that this apparatus is not limited to the connections shown. The current leads to the watt galvanometers may enter the multi-element oscillograph from the rear or from the side opposite this potential-control panel, through holes in the galvanometer compartment floor. The main precaution which should be followed is to choose the proper wattmeter winding, or the proper ratio of current transformer, so that the wattmeter fields will not be worked beyond their straight-line calibration. Since the resistance in the potential circuit may be varied over wide limits the current in the field coils may vary four to one and yet permit the adjustment to be such as to give almost any desired deflection on the photographic film. As seen from the illustration, the variable resistors, or rheostats, have no knobs and are adjusted with a screw-driver.

A convenient arrangement for controlling the current functions is to use a special series transformer with a 5-ampere secondary and a tapped primary so that currents from 4 to 100 amperes may be recorded. This transformer should not be placed in the power line, but in the secondary of standard current transformers, intended to feed indicating and recording instruments. A special current transformer of the following ratings would cover most applications met in power systems:—

Wattmeter alone—Working range = 2 to 8 amperes
Transformer—5:15—Working range = 6 to 24 amperes
Transformer—5:30—Working range = 12 to 48 amperes
Transformer—5:60—Working range = 24 to 96 amperes

Thus with the above arrangement it would be possible to obtain a satisfactory deflection on the film with any current from two up to 100 amperes. Such a transformer should not operate with a continuous current in the primary of more than 10 amperes. In most actual cases, the primary current will be in the order of three to four amperes, except for short duration transients.

### CLEARLY DEFINED RECORDS

The records which may be made with the multi-element oscillograph are so sharp and clearly defined that it is possible to drive the photographic film comparatively slowly and yet make out the envelope of each of nine waves. At a film speed of one inch per second each 60-cycle voltage or current wave and each 120-cycle single-phase power wave can be seen. A little care on the part of the operator in arranging the zero position of each light spot, and the probable maximum amplitude of each wave, will improve the readibility of the film. If this instrument was merely an improvised high-speed recorder without the refinements of a good oscillograph optical system, then it would be impossible to differentiate so many records on one film. In most cases, even though the waves overlap one another as in Fig. 9, it is easy to see the envelope of each wave.

The poly-phase wattmeter records usually are simple in form and only cross zero when the power reverses. If three polyphase-watt galvanometers are used (each one in a different alternator circuit) it is relatively easy to follow each curve even though the waves of instantaneous voltage, etc., do infringe upon the watt records. If the waves are very complex it would be better to

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use but six records, and not nine, on a slowly-moving film. However, on a more rapidly moving film, nine records are quite distinguishable. One nine-element outfit costs very much less than three three-element outfits of anywhere near comparable performance.

### LONG FILMS

The daylight-loading long-film attachment, which has been developed for the multi-element oscillograph,

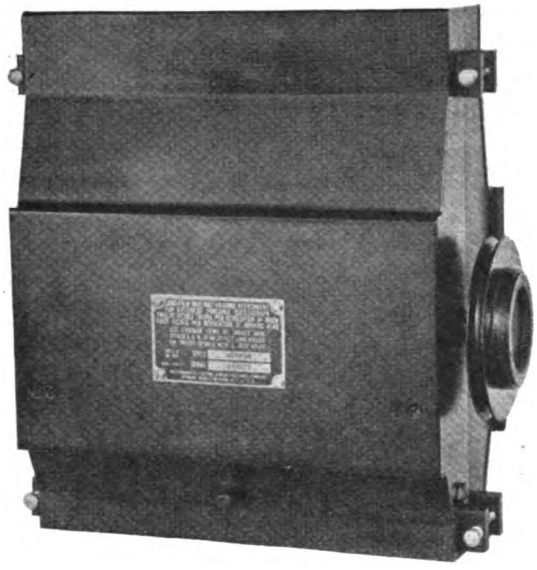
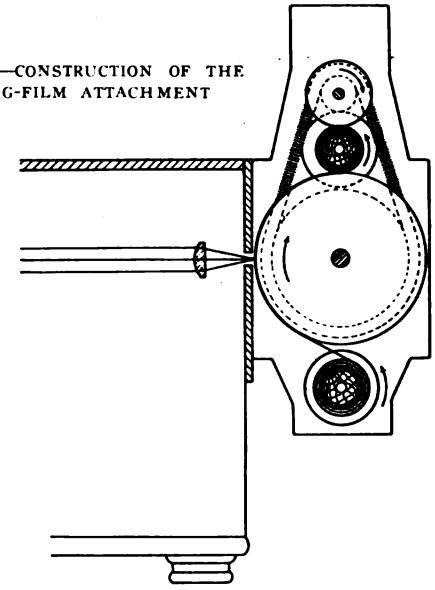


FIG. 7—THE DAYLIGHT-LOADING LONG FILM ATTACHMENT FOR THE MULTI-ELEMENT OSCILLOGRAPH

has done much to make it possible to record the whole story with sufficient detail so that the most exacting engineer will be satisfied with each part of the record. On the other hand, this film holder may be operated so slowly that its film will show as many as twenty-five chance disturbances which have affected the power system over a period of weeks or months. This long-film attachment is shown in Fig. 7. It takes roll films 6½ in. wide and 3, 6, 8, 16 or 24 feet long. Twenty-four foot records have been taken in as short a time as five seconds.

A schematic sectional view of the long-film holder is shown in Fig. 8. The unwinding spool is shown at the bottom with the unexposed film traveling up and half-way around the main drum onto the wind-up spool. The exposure to the light beams occurs as the film passes the optical slot in front of the cylindrical-condensing lens of the oscillograph.

FIG. 8—CONSTRUCTION OF THE LONG-FILM ATTACHMENT



The wind-up action of the exposed film is insured by the wind-up roller, which is driven by helical-spring belts from pulleys on the main shaft. As seen by the illustration, the wind-up spool is located between the main drum and the wind-up roller. Both this spool and the roller have extending shafts which fit into vertical grooves in the sides of the case. Thus as the wind-up spool takes on more and more film it raises up the roller above and both the main drum and the roller

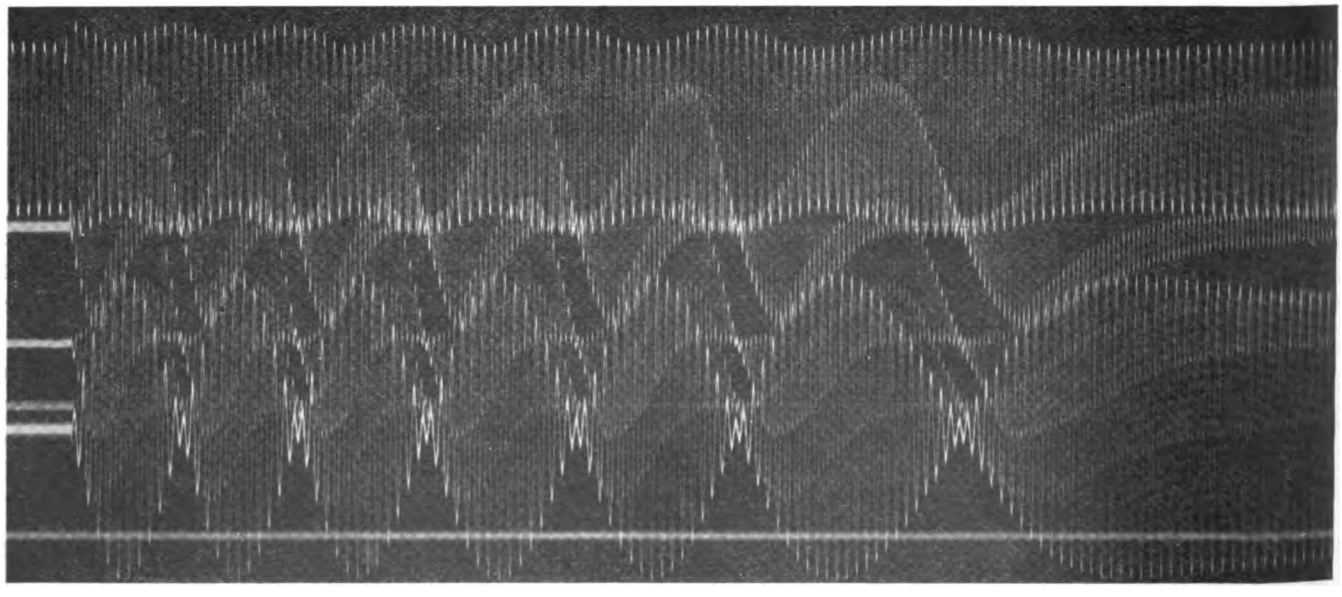


FIG. 9—TYPICAL INSTANTANEOUS WATT OSCILLOGRAM

This was taken by engineers of the Alabama Power Company and shows five instantaneous-value records: three of single phase watts, one of volts and one of amperes.

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continue to exert a good pressure on the film. Due to the greater ratio of drive, through pulleys and belts, the roller tends to wind up the film faster than it arrives. That is impossible and so the belt stretches more on one side than the other and the film is wound up very tightly and rapidly when desired. There is no slipping of the film on the drum no matter how slowly the drum is revolved. Each revolution of the drum makes one foot of record. A 3-to-1 gear reduction between this film holder and the oscillograph driving head reduces the film travel to four inches per revolution of the driving head. Other speed reductions have been previously described[3].

In Fig. 9 is shown a polyphase oscillogram taken by Alabama Power Company engineers with one of these 6-element oscillographs equipped with three single-phase instantaneous watt galvanometers, and three permanent-magnet galvanometers. The record would have been somewhat easier to analyze if a polyphase-watt galvanometer had been used. In this particular film it appears that all three watt records were quite similar except for the phase relation of the instantaneous values. This shows that for such cases, where there is no ground current, one single-phase wattmeter tells nearly the whole story of power surge, since the average power, reactive power, and power-factor vary alike in the three records.

It is clear from this film that an overload occurred which caused alternators to pull out of step, slowly at first and then faster until the circuit was interrupted by the action of a circuit breaker. Note that the current and the voltage waves are both very nearly symmetrical each side of zero, but that each power wave shifts from one side of its zero to the other as the power reverses, and that the power-factor also goes through rapid changes. The envelope of the current wave becomes practically zero several times during the record. The power-factor reaches nearly 100 percent on one side of zero and minus 100 percent on the other side of zero. The line of average power may be drawn half way between the peaks of instantaneous power, for each power record. Apparently the three power elements were not adjusted to have exactly the same calibration, since the three power waves remain consistently different in amplitude.

This record gives a good idea of how very complex waves may be and yet be distinguishable on one film. Such complexity is not needed if but one instantaneous wattmeter is used, or if a polyphase watt galvanometer is substituted for at least two of the single-phase type.

Unfortunately very slow-speed records cannot be reproduced in this article because the lines on the records are even finer than the screen used in making a half-tone engraving. The original records are clear to the human eye and show up considerable detail of each cycle when viewed with a magnifying glass. If the waves were all blurred together, due to an inferior optical system, then it would be necessary to prevent the waves of one record from overlapping those of an adjacent record. Furthermore, the oscillograph shows up any direct-current component in an alternating-current wave or in an instantaneous-watt wave. If the watt record continues for a short time after the current has ceased, that is because the series transformers are being worked too hard to take care of the direct-current component. To obtain most accurate records, it is sometimes necessary to install higher-ratio series transformers in the main line when the short-circuit current is so many times greater than the full-load current.

[3]See the JOURNAL for Jan. 1928, pp. 45 and 46.

## APPLICATION

The apparatus which has been described in these last five articles should throw wide open the field of investigation of power transients. The cost of a complete oscillograph outfit is neglible compared with the value of better operation of systems and increased loads with decreased hazards. Automatic operation on chance disturbances does not add any hazard to the system. It often saves the cost and inconvenience of a staged test on a high-voltage power system.

The whole oscillograph outfit does not take up as much room as a large radio set, and may be carried from station to station, or even operated in a transmission-line tower. The Osiso has been used, a million volts from ground, to record the corona current just preceding a 2 000 000 volt flash. Mere boys have operated these outfits with no electrical training except what they picked up in learning about radio receiving sets. An instantaneous oscillographic wattmeter is not different in its connections from an ordinary indicating wattmeter.

The series of tests on the Pacific Gas & Electric System in 1925[4], is a good example of staged operation of these portable oscillographs. The tests carried out on the Southern California Edison System in 1926 and 1927[5], required these oscillographs for automatic operation on chance disturbances. The practical aspects of these tests and calculations have been covered by papers presented before the American Institute of Electrical Engineers. Other power companies have used these instruments to good advantage. It is expected that other papers will be published, proving the increasing value of these instruments to the central station operators and engineers.

In the last several years of automatic operation not one vibrator has been damaged while in the instruments, and yet some records have shown that the deflection of the light beam went several inches beyond the film on each side. The apparatus is now much more complete and is easier to operate than ever before.

[4]See "Practical Aspects of System Stability" by R. Wilkins, *Trans. A. I. E. E.*, 1926, Vol. XLV, pp. 41-50. Also companion paper "Studies of Transmission Stability" by R. D. Evans and C. F. Wagner, pp. 51-80, and discussion, by the author, on pp. 87-88 of same volume.

[5]See *Journal A. I. E. E.* for Oct. 1927, pp. 985-994.

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## The Reason for the Auxiliary Commutating Winding on Booster Converters

A SYNCHRONOUS booster converter requires two commutating fields; the straight synchronous converter needs but one. This second, or auxiliary commutating winding on the booster machine is made necessary by the conditions which the booster imposes on the converter.

The straight converter is designed with a commutating field strength which would be entirely inadequate for operation as a direct-current generator. This is because of the fortunate circumstance that in a converter the armature reaction of the alternating current almost neutralizes that of the direct current. The un-neutralized difference is usually about 15 percent. That is, in the commutating zone, the armature reaction from the alternating current neutralizes all but about 85 percent of that produced by the direct current. The commutating field strength of the straight converter is therefore designed to overcome this remaining 15 percent armature reaction plus an additional amount necessary for the magnetomotive force required to produce good commutation.

When the booster converter is operating with the booster field unexcited, that is, with the booster neither bucking or boosting the alternating-current voltage. It is, in effect, a straight converter and requires the usual converter commutating field. The main commutating field of the booster converter is thus made the same as that of the straight converter. However, with the booster operating, different conditions exist. Suppose the converter is carrying normal, rated direct-current load and the booster is bucking, i.e., the voltage generated in its windings is in opposition to and lessening the incoming line voltage. The booster voltage is but a fraction of the line voltage—usually not more than 15 percent of line voltage. Current then flows through the booster windings in opposition to the voltage generated in them. This means that the booster is running as a motor, and is delivering torque through the shaft to the converter itself.

A synchronous machine, such as a converter, carries mechanical load by its rotor dropping back in phase position enough to permit a current to flow through the lessened impedence of its windings sufficient to produce torque to carry the load. In this case the mechanical load is principally friction and windage. Nevertheless this is sufficient to force the rotor back several electrical degrees. As the booster supplies torque to the converter, the converter is advanced in phase position and accordingly draws less current. This is to say, the direct-current load is supplied in part from the converter and in part from the booster driving the converter as a direct-current generator. We have in effect, a synchronous converter and a motor-generator set. But the point is, the alternating current flowing into the converter is less while the booster is bucking the voltage than when the booster is running idle. This means, that, for a given direct current, less than the usual 85 percent of direct-current armature reaction is neutralized. To make up for this deficiency is the role of the auxiliary commutating winding.

In like manner, when the booster is adding its voltage to the alternating-current line voltage, a reversed state of affairs exists. The booster is acting as a generator and is therefore absorbing torque through the shaft from the converter. The alternating-current in the converter is thus increased by an amount sufficient to drive the booster. The direct-current armature reaction is accordingly more completely neutralized. For example, if the booster is consuming torque equal to 15 percent of the normal electrical output, the average armature reaction would be reduced to zero. The main commutating field is thus too strong. The auxiliary commutating field must then act to reduce this.

Obviously, the strength of the auxiliary commutating field required should be proportional to the torque used or developed by the booster. As this torque is proportional to the excitation of the booster, the auxiliary commutating field strength should vary with the booster field excitation for any given direct-current load. Thus, the rheostats for the auxiliary field of the converter and direct-current field of the booster can be permanently connected together and varied as a unit.

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## Commutating Field Adjustment

ON adjustable speed direct-current motors, the commutating-pole field strength must be accurately adjusted to minimize sparking over the whole range of speed. Commutating-pole field strengths are rarely adjusted by the use of shunts. Instead, it is better to adjust them by varying the air-gap between the commutating pole and the armature.

The commutating pole air-gap is naturally large as compared with the main pole air-gap. This permits a commutating pole machine to be built with several thin spacers of sheet steel between the pole and the yoke. Then, if the commutating-pole field is found to be too strong, a spacer or so may easily be removed, increasing the air-gap and weakening the commutating flux which enters the armature. Once adjusted for the particular machine and load no change is needed.

If a shunt of the usual type were used to weaken the commutating-pole field, vicious sparking would occur during rapid load changes. The common grid shunt is practically non-inductive; the commutating field coil is highly inductive. Therefore, if a heavy load should be added suddenly to the machine the additional current would, during the change, flow through the shunt rather than through the commutating-field winding. The commutating field would not be sufficient to neutralize the increased armature reaction, and bad sparking, or even a flashover results. The same situation would exist on a rapidly decreasing load, except that the commutating

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field would be too strong instead of too weak, with the same unpleasant results.

In some few cases, however, it is necessary to use a shunt around the commutating pole windings. Some large machines, i.e., of several hundred horse-power, which have a speed range of more than about two to one or which have a relatively high reactance voltage and which are subjected to rapid load changes cannot be designed to commutate well over the entire speed range. Recourse must then be made, at the higher field currents which come at the lower speeds, to a shunt. However, a stepped inductive shunt whose impedance angle or power-factor angle, is the same as that of the commutating winding is used. Thus, the commutating field current is permitted to build up or down with the load. This shunt is so arranged that, when the field rheostat is turned out to obtain the lower speeds, sections of the commutating field shunt are automatically inserted.

## The Why of Different Temperature Ratings for Railway Motors

THE standard temperature rating of non-ventilated railway motors is 95 degrees C. rise by resistance. The rating for ventilated motors is 85 degrees C. rise by resistance. This difference of 10 degrees is not due to any mechanical or electrical difference between them, as they may be the same except for the fan on the ventilated motors. Rather, this difference results from the method of temperature testing. The standard method of test is to place the motors on the test block and run them under load, measuring the temperature rise by the increase in armature and field resistance. For the ventilated motor this approximates the actual road conditions, as the fan supplies as much air to the motor on test as it would in service. However, the non-ventilated motor, having no fan, relies principally upon the natural circulation of air around it for cooling. The air received by a motor on a moving car and on a stationary test block differ considerably. Thus, the non-ventilated railway motor can be expected to run 10 degrees cooler in service than on test.

## Direct-Current Brush Arm Capacity

THE maximum current per brush arm of a direct-current machine is limited by the brush rating and by good mechanical design of the commutator. It is often found necessary to increase the number of poles and, therefore, the number of brush arms, on a direct-current machine in order to take care of the current, even after all the other elements making for good commutation have been satisfied by the smaller number of poles. This change is made necessary because it is not possible to make a good commercial mechanical construction of a commutator which will permit sufficient brush capacity to carry the current per brush arm required by such cases. These are most likely to occur in low-voltage direct-current machines, such as are used for electrolytic purposes.

Present methods of construction have enabled commutators to be built which are mechanically satisfactory for carrying large currents per brush arm, so that it is often considered good practice to build 250-volt and 600-volt machines of the same capacity with the same number of poles.

With the usual V-ring construction of the commutators, the longer the commutator the more difficult it is to keep true, especially at high speeds and at the higher temperatures which are liable to accompany such speeds. The permissible length, as fixed by mechanical construction, has been gradually increasing as the constructions have been improved. When it is considered that the deflection of the bar is proportional to the fourth power of the commutator face length and inversely to the square of the depth of the bar, it is evident that there is a definite mechanical limitation to the permissible length of a high-speed commutator. With the two V-ring method of construction it is usually possible to build high-speed commutators of peripheal speeds from 4000 to 6000 feet per minute at lengths up to 30 inches. Longer high-speed commutators are usually built with shrink ring construction.

The permissible brush density has an important bearing in determining the limiting current per brush arm. Experience has conclusively shown that brush densities on correctly proportioned modern machines may be materially higher than the low densities found necessary on machines of the non-commutating pole type, on account of the elimination of local current, which has been accomplished by the use of the commutating pole. In such machines, the current distribution at the brush face is nearly uniform under all conditions of load, but the distribution is not exactly perfect, even in the best machines. Variations from uniformity, while approximately as much as 50 percent in good machines, are yet small compared with the variation in some of the old non-commutating pole units. In many of the old time machines, an apparent density of 40 amperes per square inch at normal load was considered as amply high; while at the present time, with well proportioned commutating poles, 50 percent higher densities are not uncommon.

The circumferential thickness of the brushes is fixed by the inherent short-circuit e.m.f. per brush, and the width of the zone of commutation. On medium capacity, low-voltage machines, where commutating conditions are favorable, the permissible brush thickness may be determined by the space available between the main poles in which lie those coils which are undergoing commutation. The danger in attempting to use too thick a brush and too wide a zone of commutation, is that the coils will approach too near the main field poles while still under short-circuit by a brush, and have excessive voltages and local currents generated in them. Under average conditions the use of a thick brush is usually permissible, so that it is not unusual to find modern, high-speed, 250-volt machines equipped with brushes 1¼ inch thick.

It is usually the case on large capacity machines of high voltage that the number of bars which the brush may span and still not have the sum of the inherent short-circuit e.m.f. reach an excessive value, will determine the permissible brush thickness. In this case, the brush thickness depends largely on the width of the commutator bars. On the basis of ¾-inch brushes and a current density of 50 to 60 amperes per square inch, experience shows that a normal rated current of about 1000 to 1200 amperes per brush arm is conservative on low-frequency machines which are designed to carry overloads for short periods, such as two hours.

## Why Insulated Rivets in Transformer Cores

UN-INSULATED rivets in transformer cores are objectionable for two reasons. In the first place if the insulation between laminations is not good, contacts between plates with a return path through the rivets may permit relatively large currents to flow. The voltage tending to circulate such currents increases as the area of the core and the magnetic density grow larger. Therefore, bolts in large transformers must be well insulated.

In the second place, if magnetic flux flows between the rivets, a voltage is generated which tends to circulate current down one rivet and back through the other. For this reason the rivets must be arranged with a line drawn through the centers of the rivets in a line parallel with the magnetic flow.

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Under the best conditions some flux will get between the rivets, and it is better therefore to insulate them.

Rivets are used only on the larger core-type transformers, where the magnetic circuit is first built up and then the coils slipped into place. The core must be bolted together to permit slipping the coils over the legs. In the smaller core-type transformer, say 200 kv-a and smaller, the punchings are built into the coils, one piece at a time. The laminations for the large shell-type transformers are also built into the coils, so that no rivets are used.

# The Transformer V Connection

C. G. VEINOTT

THE V connection of transformers is one of the most interesting in common use, being utilized probably more than any other unsymmetrical connection. To obtain a picture of how this connection operates, suppose *A* and *C*, Fig. 1, to be two equal sources of alternating voltage. Winding *A* has induced in it a voltage $E_{ba}$ which supplies a current $I_{aa}'$ to an external load $Z_1$. Winding C has induced in it a voltage $E_{bc}$ which supplies a current $I_{cc}'$ to an external load $Z_2$. If *A* and *C* are two independent sources of voltage, each functions as if it were separately supplying a single-phase load, line $bb'$ being merely a common return for the two phases.

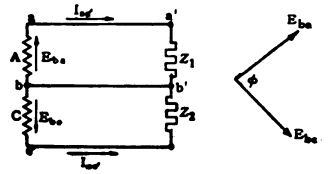


FIG. 1—TWO SINGLE-PHASE SOURCES OF POTENTIAL FEEDING TWO LOADS

If coils *A* and *C* are wound into the same generator or are in two direct-coupled generators, there will be a phase difference $\phi$ between the two equal voltages $E_{ba}$ and $E_{bc}$, depending upon the relative position of the armatures when coupled together or upon the relative position of the coils in the same machine. If $\phi$ equals 180 degrees the system is what is generally known as single-phase three-wire. If $\phi$ equals 90 degrees the system is the common two-phase, three-wire system. Also if $\phi$ is 60 degrees the system is the common V connection. This is not the same as saying that the voltage between phases is 60 degrees in the V connection. The voltages of a three-phase system, as $E_{ab}$, $E_{bc}$ and $E_{ca}$ are 120 degrees apart; hence the angle between $E_{ba}$ (which is $-E_{ab}$) and $E_{bc}$ is 60 degrees. In the general case shown in Fig. 1 angle $\phi$ may be anything. Light may be thrown on the characteristics of the V connection by a consideration of some well known features of the two-phase connection.

## TWO-PHASE SYSTEM SUPPLYING A THREE-PHASE LOAD

Assuming that the system in Fig. 1 is an ordinary two-phase system, with 90 degrees between phases, the conditions are as shown in the

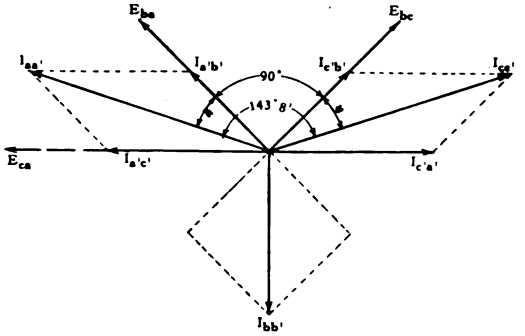


FIG. 2—VECTOR DIAGRAM OF A THREE-PHASE LOAD ON A TWO-PHASE SYSTEM

vector diagram in Fig. 2. At unity power-factor $I_a'b'$ and $I_c'b'$ are in phase with their respective voltages $E_{ba}$ and $E_{bc}$.

This is the normal operating condition of the two-phase system. The currents in the two outgoing lines are equal and 90 degrees apart. Both supply phases or transformers operate at the same power-factor, which is the same as that of the load.

The latter conditions do not hold if a third load, $Z_3$, is connected across lines *a* and *c* as shown in Fig. 3, for then a current, $I_a'c'$ in phase with $E_{ca}$, will flow as shown. Now $I_{aa}' = I_a'b' + I_a'c'$ and $I_{cc}' = I_c'b' + I_c'a'$.

From Fig. 2, it is obvious that, with a load across the outside leads, the phase angle between the currents in the two outside lines is not the same as the phase difference between the two voltages. The phase angle between the voltages is 90 degrees and that between the currents is $90 + 2\alpha$ if the impedances are equal resistances, the angle between outgoing currents is 143 deg. 8 min.; i.e., two voltages 90 degrees apart

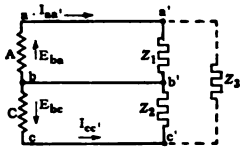


FIG. 3—A SIMPLE SYSTEM WITH TWO SUPPLY PHASE

supply two currents 143 deg. 8 min. apart Further more, although the load is a non-reactive load, the power-factor of one transformer is cos $\alpha$, or $\frac{2}{\sqrt{5}}$, leading, that of the other, $\frac{2}{\sqrt{5}}$, lagging. The total power which the two transformers can deliver to a three-phase load whose power-factor is unity, (for the particular case where $\phi = 90$ degrees) is $\frac{2}{\sqrt{5}} \times 2 \times E \times I = 0.895 \times 2\,EI$; i.e., the capacity of the two connected in this manner is only 89.5 percent of what their capacity would be if they were operating as two single-phase transformers.

## THREE-PHASE VOLTAGE, CURRENT, AND POWER RELATIONS

The V-connection is usually represented as shown in Fig. 4 (a), the vector diagram being shown in Fig. 4 (b). The connections in Fig. 4 (a) are identical with those of Fig. 1 and hence the same method of analysis will be used. Voltage $E_{bc}$ is known from Fig. 4 (b), and from the same sketch it is seen that $E_{ab}$ is 120 degrees ahead of $E_{bc}$. However, $E_{ab}$ represents a voltage which would drive a current (internally) from *a* to *b*. To follow the same procedure previously used, we must take a voltage which will drive a current from *b* to *a*; that is, a voltage which will send out a line current $I_{ba}$ on line *a*. This latter voltage is $E_{ba}$, which is the reverse of the three-phase voltage $E_{ab}$, and hence leads $E_{bc}$ by 60 degrees as shown in Fig. 4 (b).

Having shown that the two voltages from the common wire *b* to each of the other two lines differ in phase by 60 degrees, the next step is to show how these two 60 degree voltages supply three-phase currents which are 120 degrees apart. This idea is not startling after seeing that the two 90 degree voltages of a two-phase system send out currents 143 degrees apart when loaded on a three-phase load. Fig. 5 shows two transformers in V supplying a three-phase load. A delta-connected load is used because it simplifies the discussion, although a Y-connected load would yield the same results. $E_{ba}$ and $E_{bc}$, the two equal transformer voltages 60 degrees apart, are shown in the vector diagram, Fig. 6.

First, assume that the load is non-reactive. Then transformer *A* will supply to phase *p* of the load a current $I_a'b'$, in phase with its

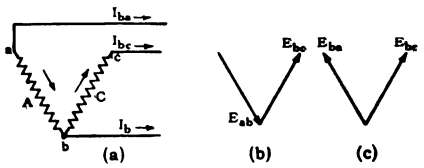


FIG. 4—THE V-CONNECTION

voltage $E_{ba}$. Similarly, transformer *C* supplies a current to phase *N* of the load $I_c'b'$, in phase with its voltage $E_{bc}$. The two transformers in series supply a current $I_a'c'$ to phase *m*, in phase with its driving voltage $E_{ca} = E_{ba} - E_{bc}$. $I_{aa}'$ is found by adding $I_a'c'$ vectorially to $I_a'b'$, and $I_{cc}'$ by adding $I_a'c'$ vectorially to $I_c'b'$. These currents are 120 degrees apart. $I_{bb}'$ is equal to $-(I_a'b' + I_c'b')$, or $-(I_{aa}' + I_{cc}')$, and 120 degrees from either of the other two line currents. In other words, the system is delivering three-phase power.

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If the power-factor of the load is other than unity, say cos $\theta$, lagging, the component vectors $I_a'b'$, $I_c'b'$ and $I_a'c'$ will all take up positions $\theta$ degrees behind their present positions; hence, the line currents $I_{aa}'$ $I_{bb}'$ and $I_{cc}'$ will move to their dotted positions, Fig. 6.

The foregoing analysis leads to the conclusion:—

If two V-connected transformers supply a balanced three-phase load, the power-factor of which is cos $\theta$ lagging, the power-factor of one transformer will be cos (30-$\theta$), leading, that of the other, cos (30 + $\theta$), lagging. If $\theta > 30$ degrees, 30 — $\theta$ is negative, or a lagging angle.

In passing, the current $I_a'c'$ seems worthy of mention. If there were no phase *m* in the load, i.e., if the load were a two-phase load, it would not exist, hence $I_a'b'$, $I_c'b'$ and $I_{bb}'$ would be the external line currents

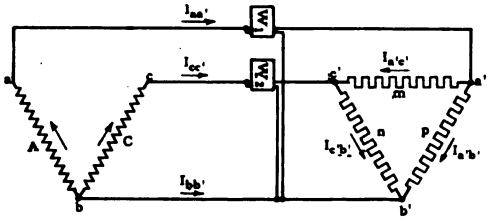


FIG. 5—$V$-CONNECTED TRANSFORMERS SUPPLYING A THREE-PHASE LOAD

and the striking similarity of the V-connection to a two-phase 60 degree system would at once be apparent. Referring again to Fig. 6, the power factor of both transformers is unity when that of the load is unity. It is the current $I_a'c'$ which does not flow through the neutral conductor (*b*), which increases the line currents up to the point where they equal the current in the neutral wire and spreads their phase difference from 60 degrees to 120 degrees, producing for all practical purposes, a three-phase system. It is the current $I_a'c'$ which reduces the power-factor of the transformers.

## POWER

It is obvious that if two wattmeters are connected as shown in Fig 5, the algebraic sum of their readings is the power supplied by the two transformers, for each wattmeter indicates the power supplied by one transformer and the total power must be the sum of the watts delivered by each transformer. It is still further evident when it is observed that,—

$$W_1 \text{ reads } E \times I \times \cos(30 - \theta)$$
$$W_2 \text{ reads } E \times I \times \cos(30 + \theta)$$
$$\text{or, } W_1 + W_2 = 2 \times E \times I \times \cos 30 \times \cos\theta$$
$$= \sqrt{3}\, E\, I \cos\theta = P$$

as in any balanced three-phase system in which power is measured by the two-wattmeter method. It hardly need be said that for power-

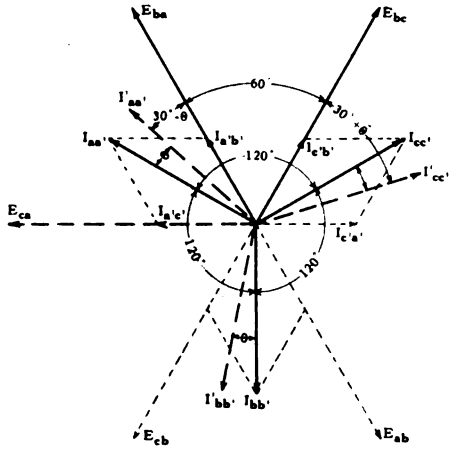


FIG. 6—A VECTOR DIAGRAM FOR THE $V$-CONNECTION

factors less the 0.5 $W_2$ becomes negative. The negative wattmeter reading means that in this event power is actually being transformed from secondary to primary of that transformer, or rather, the secondary winding becomes the primary.

It follows from the above expressions that with a balanced load, at a load power-factor of 100 percent, both transformers operate at 86.6 percent power-factor, one leading, the other lagging; that, at a load power-factor of 86.6 percent, lead or lag, one transformer operates at 100 percent power-factor, the other at 50 percent leading or lagging, respectively; that, at a load power-factor of 50 percent, lead or lag, one transformer operates at 86.6 percent, leading or lagging, respectively, the other at zero percent, leading or lagging. (This suggests a method of loading a transformer experimentally on quadrature current

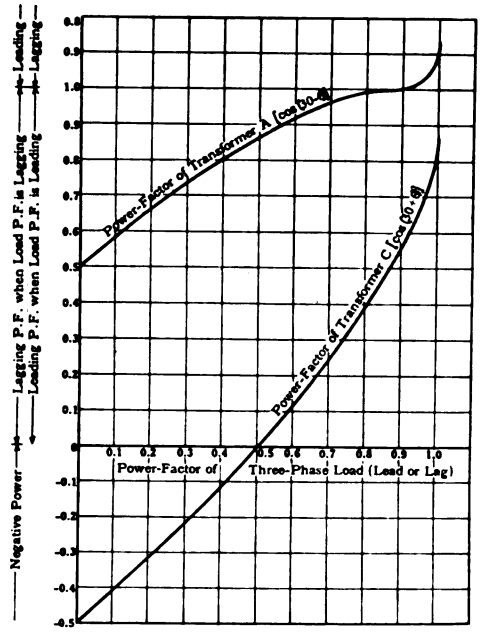
Power-Factor of Transformer A (cos 30-θ)
Power-Factor of Transformer C (cos 30+θ)
Power-Factor of Three-Phase Load (Lead or Lag)
Negative Power
Lagging P.F. when Load P.F. is Lagging
Leading P.F. when Load P.F. is Leading
Leading
Lagging

FIG. 7—THE POWER FACTOR OF $V$-CONNECTED TRANSFORMERS AT ALL LOAD POWER FACTORS.

When the power factor of the three-phase load is leading the upper curve represents transformer *C* and the lower curve represents transformer *A*.

entirely, by loading a V-system on a 50 percent power-factor load.) In Fig. 7 are shown values of true power delivered by each transformer at other load power-factors, it being assumed that the load is a balanced three-phase load. Since, at any power-factor the kv-a. load of both transformers is the same, the power factors of each transformer represent comparative values of the true power delivered by each.

From the expression,—

$W_1 + W_2 = 2\,EI \times \cos 30 \times \cos\theta = 0.866\,(2EI \cos\theta)$ it is manifestly true that the capacity of the system is 86.6 percent of that of two transformers or 86.6 × 2/3 = 58 percent of the capacity of a bank of three transformers.

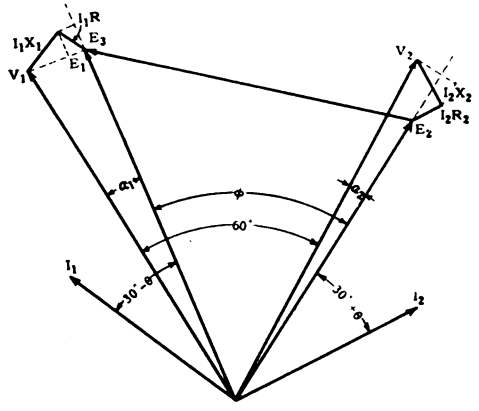


FIG. 8—THE UNBALANCING OF A THREE-PHASE LOAD ON A $V$-CONNECTION

The vectors represent unity power-factor balanced load.

## REGULATION AND VOLTAGE UNBALANCE

As the regulation of a transformer is a function of the power-factor at which it operates, the terminal voltages of two transformers connected in V must be slightly different from each other under load, for it has been shown that the power-factor of each transformer is differ

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ent. This is shown vectorially in Fig. 8, in which exciting current is neglected.

In Fig. 8, $E_1$ and $E_2$ are the terminal voltages of the two transformers under load. $I_1$ leads $E_1$ by $(30 - \theta)$ degrees, and $I_2$ lags $E_2$ by $(30 + \theta)$ degrees. Addition of the impedance drops, referred to the secondary, gives the primary voltages, also referred to the secondary, namely $V_1$ and $V_2$. These latter voltages must be equal and 60 degrees apart as they are shown. The third terminal voltage, $E_3$ or that across the open ends of the V, is the vector difference of the other two voltages and may be obtained by drawing a vector from the arrowhead of one voltage vector, $E_1$, to that of the other voltage vector, $E_2$.

For computing $V$ from a given value of $E,\theta, IR$, and $IX$, many formulas, charts, etc., have been used. Unfortunately, most of these are not readily reversible to solve for $E$, having $V$ given. The following method for obtaining these secondary terminal voltages under load is quite convenient in this case.

Resolve $V_1$, $I_1 X_1$, and $I_1 R_1$ into components, parallel and perpendicular to $E_1$; similarly, resolve $V_2$, $I_2 X_2$, and $I_2 R_2$ into components, parallel and perpendicular to $E_2$. Then, by inspection:

$$\sin \alpha_1 = \frac{I_1 X_1 \cos (30 - \theta) + I_1 R_1 \sin (30 - \theta)}{V_1} \quad ...(1)$$

$$\sin \alpha_2 = \frac{I_2 X_2 \cos (30 + \theta) - I_2 R_2 \sin (30 + \theta)}{V_2} \quad ...(2)$$

$$\phi = 60 - (\alpha_1 - \alpha_2) \quad ...(3)$$

$$E_1 = V_1 \cos \alpha_1 + I_1 X_1 \sin (30 - \theta) - I_1 R_1 \cos (30 - \theta) \quad ...(4)$$

$$E_2 = V_2 \cos \alpha_2 - I_2 X_2 \sin (30 + \theta) - I_2 R_2 \cos (30 + \theta) \quad ...(5)$$

$$E_3 = (E_1 + E_2) \sin \phi/2 \quad ...(6)$$

Expression (6) would be absolutely correct if the triangle $E_1 E_2 E_3$ were isosceles, but this is so nearly true that it is used in preference to the more cumbersome expression of the cosine law for in most cases the error involved in using this approximation is less than one-tenth of one percent.

In applying these formulas to the solution of a problem, care must be taken to use the proper algebraic signs with the term containing trigonometric functions; e.g., sin $(30 - \theta)$ is negative when $\theta$ exceeds 30 degrees and cos $(30 + \theta)$ becomes negative when $\theta$ is greater than 60 degrees; also, $\alpha_1$ or $\alpha_2$ is minus when its sine is minus and must be used as minus in formula (3). An illustrative example will show the method of application of these formulas.

ILLUSTRATIVE EXAMPLE:

Given:— $V_1 = V_2 = 100$ *volts*; $I_1 R_1 = I_2 R_2 = 1.4$ *volts*; $\cos \theta = 0.8$, *lagging*; $I_1 X_1 = I_2 X_2 = 4.0$ *volts*.

To solve for $E_1$, $E_2$, and $E_3$.

Solution: $\theta = \cos^{-1} 0.8 = 36.9°$

$30 - \theta = 6.9°$; $\sin (30 - \theta) = -0.120$;

$30 + \theta = +66.9°$; $\sin (30 + \theta) = +0.920$;

$\cos (30 - \theta) = 0.993$

$\cos (30 + \theta) = 0.392$

From (1)

$$\sin \alpha_1 = \frac{4.0 \times 0.993 - 1.4 \times 0.120}{100} = 0.0360$$

$\alpha_1 = 2.1°$ and $\cos \alpha_1 = 0.999$

From (2)

$$\sin \alpha_2 = \frac{4.0 \times 0.392 - 1.4 \times 0.920}{100} = 0.0028$$

$\alpha_2 = 0.2°$ *and* $\cos \alpha_2 = 1.000$

From (3), $\phi = 60 - (2.1 - 0.2) = 58.1°$

From (4), $E_1 = 100 \times 0.999 - 4.0 \times 0.120 - 1.4 \times 0.993 = 98.0$ *volts*.

From (5), $E_2 = 100 \times 1.000 - 4.0 \times 0.920 - 1.4 \times 0.392 = 95.7$ *volts*.

From (6), $E_3 = (98.0 + 95.8) \times \sin (58.1/2) = 94.2$ *volts**.

These results are, of course, not exact for the unbalancing of the voltages would slightly unbalance the currents, even if they were perfectly balanced at the start, and furthermore, the exciting current has been neglected, but these results should give a fair idea of the voltage unbalance to be expected in the case selected. Though derived for angles of lagging power-factor, these expressions may be used with angles of leading power-factor by merely treating them as negative angles and taking especial care to use the proper algebraic signs.

*By cosine law, $E_3 = 94.1$ volts.

EFFECT OF POWER-FACTOR AND LEAKAGE REACTANCE ON VOLTAGE REGULATION

To determine these effects, calculations were made on V-systems of transformers of the following ratings;

No. 1—333 Kv-a., 11,000 volts, 1.4 percent ohmic drop, 4.0 percent reactive drop.

No. 2—3333 kv-a., 110,000 volts, 1.4 percent ohmic drop, 6.0 percent reactive drop.

The secondary voltages under load were calculated at three power-factors by the method just described. The results are given in Table I, voltages being in percent of open-circuit voltage.

TABLE I
SECONDARY VOLTAGES ON TYPICAL V-CONNECTED SYSTEMS

| Power-Factor | $\alpha_1$ | $\alpha_2$ | $\phi$ | $E_1$ | $E_2$ | $E_3$ |
|---|---|---|---|---|---|---|
| **No. 1 Transformers** | | | | | | |
| 0.8 lag | 2.1 | 0.2 | 58.1 | 98.0 | 95.8 | 94.2 |
| 1.0 | 2.4 | 1.6 | 59.2 | 101.7 | 96.8 | 98.2 |
| 0.8 lead | 1.6 | 2.3 | 60.7 | 103.2 | 99.0 | 102.0 |
| **No. 2 Transformers** | | | | | | |
| 0.8 lag | 3.3 | 0.6 | 57.6 | 97.7 | 94.0 | 92.3 |
| 1.0 | 3.4 | 2.0 | 58.6 | 101.6 | 95.7 | 98.3 |
| 0.8 lead | 2.1 | 4.4 | 62.3 | 104.9 | 99.0 | 105.3 |

The table shows principally that a lagging power-factor tends to decrease the phase difference between the voltages $\phi$, and that a leading power-factor tends to spread the voltages. High leakage reactance accentuates this condition and causes greater unbalance of voltages as well as poorer regulation.

In this article the name V-connection has been used throughout in preference to the frequently-used name open-delta and both diagrams of connections (Figs. 3 and 4) have been drawn upright to simulate the appearance of the capital letter V. The whole idea was that the capital V will suggest two vector voltages 60 degrees apart. Once it is firmly fixed in mind that these two voltages are 60 degrees apart and that the two outgoing currents are 120 degrees apart, it is easily seen that one line current must lead its voltage by 30 degrees and the other current must lag its voltage by 30 degrees. This condition is for a unity power-factor load. Thus both transformers must work at a poor power-factor even when supplying a non-reactive load, and this is why the capacity of two transformers in V is less than the sum of their single-phase capacities. And since the transformers work at different power-factors, their voltages under load must be different, due to regulation.

# Why Wavy Strips are Used as Transformer Coil Spacers

THE fundamental purpose of spacing strips between transformer coils is to increase the coil area exposed to the cooling oil. Straight strips would, of course, do this and could be made without special cutting dies. However, wavy strips have two advantages over the straight ones. The coils, being held apart by the strips, need bracing to prevent their moving out of place. A straight strip covers only one or two conductors, depending on its width, and the conductors between it and the adjacent strips have no support and may move under a severe overload or short circuit. Obviously, the wavy strips do not have this fault.

Then, too, the wavy strips circulate the oil back and forth across the conductors so that every conductor comes in contact with the moving stream of oil. When straight strips are used the conductors under the strips have no chance to come into contact with the moving oil. Of course, the wavy strips cut down somewhat the natural circulating ability of the oil, but in actual practice the difference is negligible.

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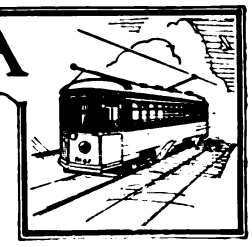
# RAILWAY OPERATING DATA

THE ELECTRIC JOURNAL

February 1928

The purpose of this section is to present accepted practical methods used by operating companies throughout the country.

The co-operation of all those interested in operating and maintaining railway equipment is invited. Address R. O. D. Editor




# Noise Reduction

In these days much money is being spent, and thought given to make the street cars more attractive and comfortable, primarily to increase the number of car riders. In this connection operators should not forget that today the people in discussing comfort make their comparisons largely with automotive equipment on rubber tires which implies quiet operation. Thus, to be progressive and up to date, street railway operators must give consideration to the subject of noise reduction not only from the standpoint of satisfying

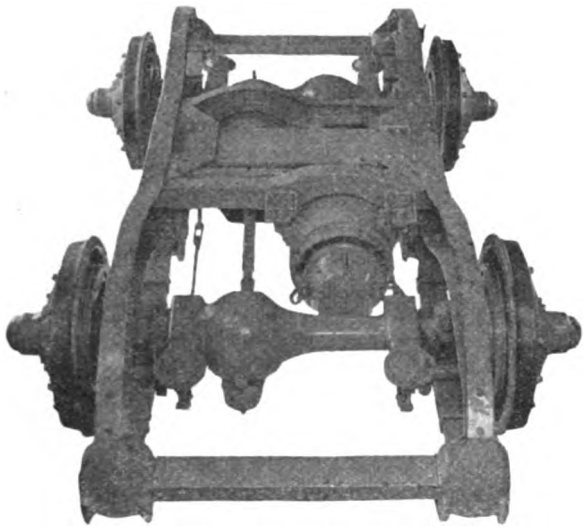


FIG. 1—A WORM DRIVE TRUCK

Which minimizes noise and reduce the unsprung weight.

the demands of the travelling public for increased comfort but as an economic measure as noise is coincidental with wear and tear on the equipment.

### EQUIPMENT NOISES AND THEIR REMEDIES

The one outstanding thing operators can do to reduce noises is to better maintain their equipment. Most railway men responsible for equipment upkeep realize this fact, but as

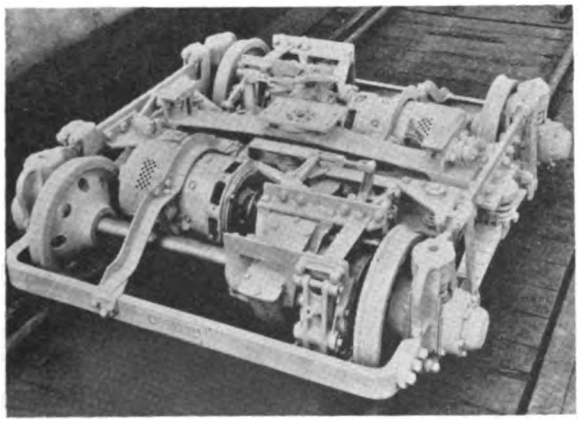


FIG. 2—A TRUCK FITTED WITH A UNIQUE MOTOR AND BRAKE ARRANGEMENT TO MINIMIZE NOISE

yet they have not been able to completly sell this idea to their managers, at least to the extent that they are given the required increase in their budgets. Various operators and engineers who have given this matter considerable thought and much time in conducting experiments have found the following sources of noise and remedies.

a—*Car Bodies*—Light weight cars are less noisy than the heavy ones. The sash panels, ceilings and floors should be lined with a noise insulating material such as open-mesh cotton scrim.

b—*Center plates and side bearings*—These should be well lubricated.

c—*Doors*—Improved mechanism should be used and kept well lubricated.

d—*Windows*—Smaller windows fitted with heavier glass and spring sash supports are preferable.

e—*Trucks*—The use of fewer parts and better, more resilient springs reduce noise. Skirts around trucks also help to confine the noise. Reducing the unsprung weight, improving the maintenance and spraying the trucks with oil are helpful.

f—*Wheels*—The wheels should be smooth and have a round tread and should be padded.

g—*Foundation brake rigging*—Better fitting of detail parts and improved maintenance minimize these noises.

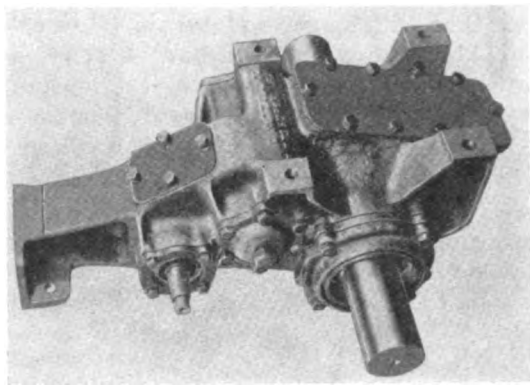


FIG. 3—A NEW TYPE OF DOUBLE REDUCTION GEAR UNIT

For high speed light weight motors which are entirely spring supported.

h—*Air Compressors*—Resilient supports for mounting and better maintainence are important for noise reduction.

i—*Covers*—Keep covers tight.

j—*Gears*—The use of pads, helical gears and semi-fluid lubricant are important.

k—*Gear centers*—Better maintenance of armature and axle bearings is suggested. 1/16 inch maximum allowable spread is recommended.

l—*Motor brushes*—Use high-grade electrographitized carbons. They should have a neat sliding fit in the brushholder carbon box.

m—*Tracks*—Better maintenance is essential.

### TRACK CONDITIONS

The A.E.R.A. Committee on Way Matters in connection with their study of the reduction of noises in car operation, subdivided the noises with which they are concerned and for which they are responsible, as follows:

*Noises Due to Degree of Track Maintenance*—It is the opinion of the committee that the standard of degree of track maintenance may be blamed for the largest percentage of the objectionable and disturbing noises directly attributable to track conditions. Under this heading are the following general noise making conditions:—

1—Special trackwork
2—Imperfect rail joints
3—Broken rails

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# Can other stations enjoy records like this? YES!

*In one station . . .*
Turbine ran 7 years
*on one charge of oil*

50 barrels of Gargoyle D.T.E. Oil Light—well-known product of the Vacuum Oil Company — was installed in the 30,000-k.w. turbine of a Michigan public service station.

After 84 months the original charge of oil was still in service, with no time out charged to lubrication. The only requirement has been make-up oil to care for normal losses and periodic oil conditioning while out of service for causes other than lubrication.

Recent analysis of the oil shows its condition so good it can be safely continued in service.

* * *

A station that can run 7 years without enforced stopping to remove sludge can almost forget what sludge danger is.

Probably the most important characteristic of Gargoyle D.T.E. Oils is their proved ability to resist sludge-forming agents.

Why take risks in your turbine lubrication?

*In another station . . .*
cooler tubes
*kept clean 8 months*

Danger of shut-downs threatened in a New York State electrical service station with a competitive oil in use.

Bearing temperatures were high. The cooler tubes of the turbines were quickly coated. Tubes were pulled twice a month, regularly, for cleaning.

Gargoyle D.T.E. Oil was installed to remedy the frequent complaint: "out of service to clean oil coolers."

8 months later the Chief Engineer reported, "No difficulty from coating of cooler tubes. Original charge of Gargoyle D.T.E. Oil Light still in service."

* * *

"They reduce the chances of service interruptions"—that is the outstanding reason why Gargoyle D.T.E. Oils have earned their reputation for reliability and economy in use.

Throughout the world these are the most widely-used turbine oils.

Why take risks with your turbine lubrication?

A careful turbine operator never willingly gambles in any factor that may affect the reliable operation of his turbine. Nor does the Vacuum Oil Company take any chances when producing oils correct for turbines.

From the selection and treatment of crude oil to the finished lubricant in use, our chemists and engineers have reliable turbine operation always in mind.

We maintain an extensive technical department to keep in touch with every new development in turbine construction and turbine lubrication.

Our turbine knowledge, and turbine oils are at your disposal.

* * *

NOTE: On request we will send you, without obligation, our authoritative treatise: "Steam Turbine Lubrication." Write for your copy.

# Vacuum Oil Company

*Headquarters:* 61 BROADWAY, NEW YORK

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*A grade for each type of service*




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4—Corrugated rails
5—Sand or other foreign matter on rails
6—Rails loose on ties
7—Squealing of car wheels on curves
8—Obstructions in rail grooves.

This committee urges upon operators the importance of maintaining their tracks in the best possible condition. It is their opinion that welding of special track work, cupped rails, rail joints, etc., greatly reduce noises due to track conditions, especially if the welds are properly ground. This practice is strongly recommended to all operators not now making use of it.

*Noises Due to Type of Track and Pavement Construction*—This committee offers for consideration in connection with track construction and maintenance the following, to lessen vibration and noise:—

1—The installation of block pavement with an asphalt mastic filler in the joints instead of cement grout.

2—The use of an asphalt mastic rail filler along the rail web where the balance of the pavement is laid with cement grout.

3—The use of continuous flange bearing special track work and unbroken main line frogs in such locations as possible.

4—Consideration of the noise emanating from vehicular traffic, when making a selection of track pavement.

5—Special consideration in selection of type of pavement contiguous to churches, schools and hospitals.

6—Special attention to greasing curves and the use of the most suitable grease for this purpose.

7—Reasonable care in the removal of all obstructions from the rail grooves.

### INSTRUMENTS FOR MEASURING NOISES

To measure the intensity of the various car noises, a device in the form of a permanent magnet type radio loud speaker is generally used. Alternating currents generated in the loud speaker mechanism by sound waves striking on the diaphragm of the loud speaker are amplified by vacuum tubes, then rectified and recorded on a graphic direct-current voltmeter. This apparatus may not interpret the sound waves in the same manner as does the human ear, but it does give comparative values provided the noises are of the same character.

JOHN S. DEAN.

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# The JOURNAL QUESTION BOX

Our subscribers are invited to use this department as a means of securing authentic information on electrical and mechanical subjects. Questions concerning general engineering theory or practice and questions regarding apparatus or materials desired for particular needs will be answered. Specific data regarding design or redesign of individual pieces of apparatus cannot be supplied through this department.

To receive prompt attention a self-addressed, stamped envelop should accompany each query. All data necessary for a complete understanding of the problem should be furnished. A personal reply is mailed to each questioner as soon as the necessary information is available; however, as each question is answered by an expert and checked by at least two others, a reasonable length of time should be allowed before expecting a reply.

2802—CONTROL OF OUTDOOR SUBSTATION AND LAYOUT OF FEEDERS—A system consisting of three 37½ kv-a transformers in an open substation is on the roof of an industrial plant; ungrounded secondaries are to be delta connected to a three-phase 220-volt bus and neutrals to a three-bar 110 volt bus; one six-wire feeder is connected to buses to carry the entire load of 110-volt lights approximately balanced on each phase and between the 110-220-volt wires. 1—What is the preferable method of controlling and protecting this six-wire feeder from beneath the substation and inside the building? 2—Would there be any inductive heating effect from the use of the circular type of hanger for this feeder wherein the three 220-volt wires would be triangularly disposed between porcelain insulator clamps while the three 110-volt wires would be similarly mounted in a second set of hangers parallel and close to the 220-volt wires, the branch circuits being tapped off two 220 and one 110-volt wires to panel boxes? 3—Would it be preferable to mount the wires in two horizontal rows with the 110 volt wires above the 220-volt wires, using two cast metal hangers bolted back to back, having split porcelain insulators secured with metal caps? The branch circuits in this case would tap off one 110-volt wire on top and two 220-volt wires beneath. J. T. (OHIO)

(1) It is not considered desirable to try to control or protect the 6-wire feeders mentioned above between the secondary terminals of the transformer bank and the point from which the individual single-phase, three wire lighting feeder radiate. In the event of trouble on this section of the six-wire feeder, the high-tension switching equipment should be such that the current will automatically be removed from the transformer bank before any considerable damage occurs. In the event however, that some main line protection on the six-wire secondary feeder is desired, a six-pole fused knife switch of the single throw variety and of 300-ampere capacity may be installed and fused for the full 300-amperes on each of the 220-volt poles and for 150 amperes on each of the 110-volt poles. It is desirable, however, to have individual feeder fused switches of the three-wire variety on each single-phase three-wire tap off the six-wire main feeder. Each of these main fuses must be of sufficient capacity to carry their required load without heating. Where the neutral wire of a single-phase, three wire circuit is ungrounded as in this case, it is not considered advisable to omit the fuse in the neutral although this fuse should be smaller than either of the fuses in the 220 volt line. (2) In the event that the high tension side of this transformer bank is to be used for controlling this six-wire feeder as mentioned above, fuses should be installed of sufficient capacity in the high tension substation that it would take practically a short-circuit beyond the transformer bank to blow them, and these main fuses should have sufficient rupturing capacity to successfully interrupt the high-tension current. (3) There would be no inductive heating effect from the use of any type of metal hanger for this six-wire feeder. All six conductors would be grouped together in a metal conduit from the secondary terminals of the transformer bank to the junction point. If the metal conduit will not inclose all six wires, any type of hanger can be used which will give a good arrangement of six conductors. (4) The suggested arrangement of two horizontal rows of three wires each with the 110-volt wires above the 220-volt wires, seems to be as good as any. (5) The high-tension connection of these three transformers is not given but, assuming it to be delta, there is one precaution that should be taken in a three-phase, six-wire lighting scheme and that is the possibility of one of the three delta-connected transformers may fail, thus leaving an open-delta condition which would actually remove the neutral from one three-wire, single-phase lighting circuit. If the lights on this circuit were exactly balanced, this condition could exist without damage to the lamps. In the event however, of some unbalancing of this circuit, the condition of unbalanced secondary voltage would exist which might be of a sufficient degree to burn out all the lamps of one side of this circuit and hence extinguish those on the other, due to a lack of current carrying material. This condition should be anticipated and arrangements made in the layout so that the circuit which would be effected by an open-delta connection of transformers could be temporarily shifted over to one of the other circuits which would not be effected by this open-delta condition. (6) If the high tension transformers were star connected and one transformer failed, unless a grounded neutral system on the high tension side prevailed, single-phase secondary service on a reduced voltage would be the result. Approximately two-thirds of the lamps could be used without overloading the transformer excessively. With a grounded neutral, three-phase, four-wire high-tension system in service, however, if one transformer fails, normal single-phase, three-wire service would result on two of the three-wire circuits and the lamps

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on the third circuit would have to be distributed between the two good circuits in order to keep them burning.

F. A. L.

2803—TRANSFORMING FROM THREE-PHASE TO SINGLE-PHASE—In Taylor's "Transformer Practice," 2nd Edition, p. 82, there is a statement as follows: —"Three-Phase to Single-Phase Transformation.—An interesting three-phase to single-phase arrangement is given in Fig. 75. For this service three single-phase transformers or their equivalent (somewhat special in their construction) are required, the magnetizing current being much stronger than that used in the ordinary static transformer in order that the iron may be supersaturated. This modification will result not only in satisfactory transformation of voltage and current, but transformation of the frequency as well. "With three transformers connected as shown in Fig. 75, the secondary windings would under ordinary conditions show no e.m.f. across A-C; but if the iron is saturated the secondary becomes so transformed that an e.m.f. is obtained having *3f* or three times the frequency of the primary. "The advantage of this arrangement is felt where arc and incandescent lighting is required and where the

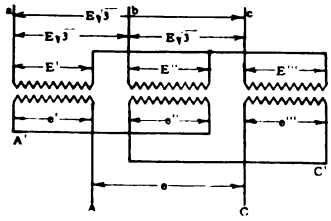

FIG. 2803—FIG. 75 OF TAYLOR'S "TRANSFORMER PRACTICE"

frequency is 15-25. The constant extension of electric traction on railways operating at these frequencies has resulted in the use of polyphase lamps and the triple frequency transformer arrangement. Single-phase railways are much more general than three-phase, and, therefore, it is really more important to be able to increase the frequency of single-phase than of three-phase current. "Also, in general, three-phase high voltages and energy are transmitted long distances to electric traction plants at a frequency of 60 cycles. It is therefore important from several viewpoints to be able to transmit electric energy at, say 60 divided by 3 = 20 cycles and single-phase; thus reducing the voltage drop due to the higher frequency, and reducing cost of line construction, insulators and its maintenance in general." As the article does not go into details I would like to know a little more about the proposition. First, I will tell you what I would like to do. Would it be possible to take any commercial transformers, preferable instrument, and make them do the job? Namely, transforming 440 volts, 60 cycle, three-phase to anything from 80 to 125 volts, single-phase at close to 20 cycles? We have a remote telephone system in the Seminole oil field, a manually-operated board, magneto-type 30 line. The operator is very busy and a ringing machine would help matters considerable. However, the cheapest we can buy is about $100 and it is a motor-generator set, which in no way would compare with the transformer proposition in the view of maintenance. We have both 220 volt and 400 volt instrument transformers in stock. If 220 volt transformers were connected to the 440 volt circuit in star, would not the overvoltage be enough to supersaturate the core? If so, would the transformer stand continuous service from a heating standpoint? Would not an instrument transformer be more liable to stand the service than the ordinary static transformer? The diagram shows the secondaries connected in series, would the ratio not be higher than the standard ratio in a single-phase connection? If the voltage would be too high for the 220 volt transformers, would the 440 volt transformers operate connected in delta on the primary side?

C. C. (OKLA.)

The last three sentences of the quotation are quite confusing. They may be correct in themselves but apparently have no connection with the rest of the quotation nor the subject under discussion. It is well known that the hysteresis in the core of a transformer introduces a third harmonic component. The connections shown in the figure balance out the fundamental frequencies, leaving, across the terminals *AC*, zero voltage at the fundamental frequency. Hence the only voltage across *AC* would be at the third harmonic or harmonics of multiples of three. With the usual transformer the third harmonic voltage would be much greater than any of the higher harmonics hence it could be assumed that voltage *AC* would be at triple normal frequency. As the third harmonic voltages in the three phases are all in phase with one another the voltage would be single-phase at triple frequency. The magnitude of this voltage would depend upon the shape of the hysteresis loop and hence would be increased by working the transformer at high excitation. With the shape of the hysteresis loop known, the magnitude and wave shape of this third harmonic voltage would be readily calculable. Under some conditions it might equal the fundamental phase voltage. Hence so far as secondary voltage is concerned it might be considered that the connection shown in Fig. 75 transforms from three-phase to single-phase at triple frequency. However, when it comes to taking any load from the secondary circuit conditions are different. Current at single-phase triple frequency could of course be obtained, but the voltage regulation would be exceedingly poor as would also the primary power-factor. Also the size of transformers required to obtain any real secondary load under these conditions would be excessive. In other words while this connection may have some theoretical interest, for actual application it is uneconomic and impractical. Furthermore, it must not be assumed that this method transforms from three-phase power to single-phase power, as the power-factor relations in the primary circuit with a load of this type would be worse than would be obtained if a single-phase load were taken directly from one of the phases. In other words there is no way of getting around the fundamental fact that polyphase power is uniform and single-phase power is pulsating and it is not possible to transform from one to the other without some means of storing and releasing energy twice during each cycle. The above discussion will show that you have been misled by the latter part of the above quotation. The transformation cycle discussed is quite irreversible. That is, although it is possible with a three-phase 20 cycle voltage applied on the primaries to take off a single-phase 60 cycle voltage from the secondary, it is quite impossible to reverse this process. If you apply single-phase voltage at 60 cycles to *AC* in Fig. 75 you will get single-phase voltages at 60 cycles across *E'*, *E''*, and *E'''*, on the primary and furthermore these three voltages will all be in phase with one another so that the voltage from *ac* or *ab* will be zero at 60 cycles. There are various ways besides the one shown of stepping up the frequency by means of transformers, some of which are commercially applicable. See, for example, an article on "Static Frequency Doublers" in the JOURNAL for April 1921, p. 122. There is no way, however, of reducing the frequency by means of transformers alone.

C. R. R.

2804—TRANSMISSION SYSTEM SPEED CONTROL—In Mr. Jollyman's article in the June, 1927 JOURNAL on "The Speed Control of a Transmission System" there are two things he didn't cover that I would like to know. 1—Does a system ever have two stations with their governors cut in at the same time? I have been told that they do not because they might start a swing, first one governor taking all the load and then the other one. 2—Would the stored energy in a system like Mr. Jollyman speaks of prevent anything like that? I have had two large hydro reaction turbines cut in at the same time and didn't notice any swing.

J. J. H. (CALIF.)

(1) Our system frequently operates with the governors cut in on two or more stations at the same time. When this is done the governors must be set so as to have an inherent drop in speed from no load to full load of about four percent. When so adjusted there will be no swinging of load from one station to the other. If the governors are set with too small a drop in speed from no load to full load, such as one percent, there may be some swing in governor action from one station to another. (2) The large amount of stored energy in the flywheel effect of a large system tends to reduce the rate of change of speed upon a change of load and therefore gives the governors of the prime movers more time in which to make a change of input. The slow rate of change in speed facilities governor action and assists in preventing any swing as between several units that may be governing. The reduction in the tendency of load to swing from one governing unit to another is more dependent on the adjustments of the governors than it is on the flywheel effect of the system to which they are connected.

## CORRECTION

In the article on "New 40 000 Kilowatt Turbines for the Duquesne Light Company" in the January JOURNAL p. 36 the turbine shown in Fig. 1 is rated at 1800 r.p.m. instead of 3600. Also Figs. 3 and 4 should be interchanged.

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# THE ELECTRIC JOURNAL

VOL. XXV MARCH. 1928 NO. 3

**How Choose a Motor**

The three questions which a purchaser asks in buying an induction motor are: How much will it cost? What will it do? How soon can I get it? In the salesman's language these are called price, performance and delivery. It is concerning the second of these only that there can be any question as to interpretation of statements or figures.

What are the governing characteristics of an induction motor and how is its excellence measured and compared? The size or horse-power of the motor is not one of these, for the reason that different jobs have different requirements. Neither are the phase, frequency, voltage or speed, because these are fixed either by the supply circuit or by the requirements of the job. This leaves the following characteristics which are within the control of the designer and which can be studied and compared as a measure of the excellence of the performance of the motor: efficiency; starting torque; maximum torque; heating; power-factor; starting current; air-gap; insulation. To these, usually, are added mechanical features such as:—bearing dimensions, and whether bearing leaks oil which might be detrimental to the insulation; mechanical vibration; noise; form of slots and windings; appearance. Little attention is usually paid to certain other important characteristics, such as reliability, low upkeep, ease of repair and minimum attention, as they can be taken for granted in the product of a reputable manufacturer.

In comparing the performance of two different types of motors, it is urgent that the comparison be complete, as a partial comparison of one or two characteristics may be very misleading. For example, it is by no means safe to assume that one machine is superior to another because it has a better efficiency alone, or a better power-factor alone, or a greater maximum torque (sometimes called pull-out). The reason for this caution is that usually any one particular characteristic can be favored at the expense of others. For example, high efficiency may be obtained at the expense of low starting torque and high starting current, by putting insufficient resistance in the bars and rings of a squirrel-cage rotor. Also, a high starting and maximum torque may be obtained at the expense of low power-factor and low efficiency by decreasing the number of turns in the stator winding, which increases the magnetic field and hence increases the magnetizing current and the iron loss. Also the power-factor may be somewhat improved by cutting down the air-gap, or clearance between the stator and rotor; but this means that a much smaller bearing wear will wipe out this clearance entirely. Further instances could be given which emphasize the fact that when the performances of motors are compared all of the characteristics must be considered or an erroneous conclusion may be drawn. A. M. DUDLEY

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**Short-Hand Mathematics**

Sir Isaac Newton in his gravitational calculations required a new method of analysis. Generalized and systematized this became what is now known as calculus. In the same way C. L. Fortescue, in his studies of unbalanced polyphase circuits, needed a simpler and more systematic method of analyzing unbalanced circuit problems, and developed the method of symmetrical components. This method of analysis was used by Fortescue, Gilman, Peters, Slepian and others in studying power in unbalanced circuits; in analyzing the characteristics of single-phase motors, polyphase motors with unbalanced voltages, synchronous motor-generator sets, phase converters and phase balancers for single-phase railway electrification; in fact, it is a splendid tool for studying rotating machines of all kinds. It was first publicly described in June, 1918. It has been extensively used by Evans and Wagner in their studies of transmission line stability and short-circuit calculation. It has been used by Bekku of Japan, in various studies of machine characteristics and especially of transients. It has been responsible for the development of entirely new types of relays, measuring instruments and voltage regulators from which results entirely impossible with older instruments have been obtained. In general, it has been proved extremely useful over a wide variety of applications by a relatively small number of engineers in all parts of the world.

Great credit is due to Mr. Fortescue and his associates for having developed this new method of simplifying the calculation of otherwise extremely complex problems, whose solution is nevertheless of the utmost importance in modern electrical engineering; and also to Messrs. Wagner and Evans for presenting to the engineering public for the first time in readily understandable and useable form an explanation of this method of analysis. While they require a certain amount of study, we feel confident that this series of articles, the first of which appears in this issue, will prove of great value to engineers having to deal with unbalanced polyphase circuits of any kind. CHAS. R. RIKER

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# 220 Kv Lightning Arresters

## A New Approach to an Old Problem

A. L. ATHERTON
Lightning Arrester Engineer,
Westinghouse Electric & Mfg. Co.

The decision to use lightning arresters on the terminal stations of the Conowingo-Plymouth Meeting line is of interest mainly because it constitutes a departure from the previous general conception that lightning arresters would not be needed, or at least that they would not be economically justified, at 220 kv; and in a secondary way because the arresters are the largest yet designed. A third, and rather unanticipated interest, comes from the study which preceded the decision, the effect this study may have on the future attitude toward this type of problem and the new ideas brought out, and the old ideas crystalized, by the study. While it is this third point with which we are chiefly concerned here, it may be worthwhile to review the other two in order to establish the proper perspective.

FOR YEARS it has been quite generally accepted that there is an upper limit of operating voltage above which lightning arresters should not be used. These ideas were originally based on the thoughts that lightning voltages in transmission circuits will be substantially the same regardless of the operating voltage; and that, since apparatus insulation strength is increased as operating voltage is increased, it is to be expected that at some upper voltage limit apparatus insulation will successfully withstand these voltages. The fact that line insulators have continued to flash over as operating voltages and line insulation were increased, made it clear some time ago that the highest of lightning voltages exceed the strength of any insulation in use.

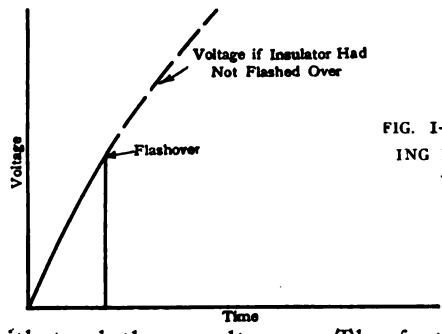


FIG. 1—CONDITIONS CAUSING EXTREMELY RAPID VOLTAGE RISE

The thought was then advanced that these higher values of lightning voltage occur less frequently than do the lower values, so that as operating voltage is increased, the danger times are less frequent, decreasing the need for arresters. It has been further pointed out that the cost of arresters per kv of rating increases quite rapidly as the voltage rating is increased. Taking this fact together with the decreasing frequency of occasions when the arrester is needed, the conclusion has been drawn that, even though the original thought that arresters are not needed may be incorrect, they will not be economically justified at the higher voltages.

Recent difficulties with lightning flashover of lines insulated for the highest voltages, and with lightning failures of high-voltage transformers and flashovers within station yards, have led to further scrutiny of the earlier conception. The tremendous importance which must be attached to continuously dependable service from large stations operating at high voltages offsets any thought of lack of economic justification for any reasonable expenditure for effective relief measures. The question is not, "Can we get some relief or cure at a price we can afford to pay?" but "Are the lightning voltages actually going to be dangerous, and can we get some relief?"

The klydonograph has thrown some added light on the general question as to what the voltages may be expected to be, and how frequently they may be expected to occur. Voltages as high as 2000 kv have been registered on insulator strings of 14 units. In the laboratory, the only way such voltages can be reached on such strings is to apply the voltage at an extremely rapid rate, so that the voltage overshoots beyond the crest value of 60 cycle flashover due to the time required for flashover to take place. The only way such rapid rises of voltage in actual service can be conceived is that they take place when the voltage to which the line potential would rise, if it were not for the flashover, is very much above the measured value.

It is known that, if a surge voltage applied to an insulator lasts longer than approximately one microsecond (one-millionth of a second) the flashover value would be at least practically the same as the crest value of 60 cycle dry flashover voltage. It is also known that, for the voltage to rise to double this value, as in the case of the 2000 kv values registered for 14 units, the rise must have been extremely rapid. It is believed that it can only be so rapid when the conditions are as indicated in Fig. 1. If these ideas are correct, it appears that the upper limits of lightning voltages which may be reached are considerably beyond the upper limits of line insulation which is contemplated at the present time. The frequency of occurrence of such extreme voltages is sufficient to constitute a very definite hazard to proper system operation.

These thoughts have led to a new conception as to the relation of lightning protection to systems, at the higher voltages. This conception is based on the general thought that, on account of the great extent of the transmission line, as compared to the station, a very large share of the disturbances will

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originate on the line, and can reach the station only by traveling along the line. The line insulation thus constitutes an upper limit for the voltages which may reach the station. Even in the cases of those over-voltages which originate directly at the station, the line insulation offers a limit after the time delay required for the transmission of the disturbance to the line and the return into the station of the reflected wave. Accepting this limit, the need for protection is dependent on the relation of the insulation in the station to the insulation on the line.

Here an uncertainty is encountered. Such over-voltages usually affect switching equipment by flashover. This is the same kind of occurrence as takes place when a line insulator flashes over. We may measure the upper limit of insulation strength for the line and switchgear insulation in the same way and place some reasonable dependence on the results. Insulation within such apparatus as transformers, however, is quite different. Failure here usually occurs by puncture. Puncture of solid insulation is an altogether different process from flashover around an insulator. The ratios of strength

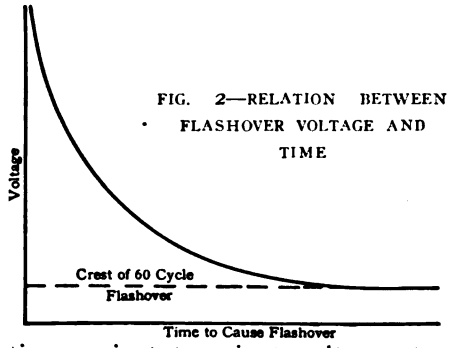


FIG. 2—RELATION BETWEEN FLASHOVER VOLTAGE AND TIME

of insulation against transient voltages to strength against immediate failure on 60 cycle voltage are radically different. Moreover, in the case of flashover, if the transient does not cause failure, no harm is done. In the case of solid insulation, however, it is quite conceivable that a transient voltage one-half high enough or one-half long enough in duration to cause failure will cause a partial failure, and if repeated two or three times will cause an actual puncture and will be followed by destruction of the insulation. This cumulative effect of deterioration of solid insulation under the influence of transient voltages can be expected to shorten the life of apparatus unless the preventive or protective means are effective.

When considering the effect on insulation within the station, another point must be kept in mind. If the station is at the terminal of a line, that is if the surge enters the station over one line, and if there are not also connected to the bus other lines in which simultaneous voltages are not induced, reflection takes place at the station and increases to nearly double the initial value of the incoming voltage. This increased value of voltage is first applied to the apparatus within the station, so that, for such a condition, equal insulation strength does not ensure against trouble. This condition of connection at a terminal point is perhaps an unusual one in the present scheme of transmission circuits, and for the more usual condition, in which the station may be considered a way station instead of a terminal, the insulation may be considered on the basis of parity.

Let us look into the statement made above that insulation strength, so far as flashover is concerned, may be considered on the basis of the crest value of 60 cycle dry flashover. Any insulation flashover requires some time; the higher the voltage applied the less the time. Laboratory tests have indicated that, if the transient voltage endures for longer than one microsecond, the flashover value is approximately equal to the crest value of 60 cycle flashover. If the voltage is to be applied for less than this limiting time, a higher value of voltage is required to cause flashover. The general nature of this relation is shown in Fig. 2.

The duration of a transient at a point on the line is determined by the amount of line charged, the rate of cloud discharge, and the rate of travel of the transient along the line. This rate of travel is approximately the same as the speed of light or approximately 1000 feet per microsecond. Even if the cloud discharge be considered as instantaneous, it is difficult to conceive that the charged length is limited to 1000 feet. In other words, most transient voltages will have a duration greater than one microsecond.

Hence, so far as flashover of insulation by lightning voltages is concerned, we are interested primarily in the crest value of 60 cycle dry flashover voltage. In the present state of the art, we do not know how to make a comparison between the values for a solid insulation and the values for flashover. It is known that, if a short-time voltage is applied to a piece of solid insulation, such as is used within apparatus, and if this voltage lasts for possibly 20 microseconds, the value to cause failure is appreciably higher than the test voltage of the apparatus. Somewhat lower voltages, of the same duration, will cause failure if applied repeatedly, or in other words, each application causes some deterioration.

For new apparatus, the safe value of voltage is probably well above the test values. As service with the apparatus continues, the insulation deteriorates, due to mechanical stresses introduced by alternate heating and cooling, due to overheating and to natural changes with time. As a limit the insulation may be assumed ultimately to reach a state where any overvoltage beyond the normal operating value will cause trouble, and on this basis, the upper limit is the crest value of voltage normally applied. Some value between that for new apparatus and that for apparatus which is about to fail is the proper value to consider.

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Present-day lightning arresters do not prevent the rise of overvoltage values beyond line voltage, but permit some increase. Possibly the proper dividing point to assume, for the moment, will be the value determined by the kind of protection available.

From these considerations the following conclusions may be drawn:—

1—Voltages high enough to cause trouble are to be expected on any circuit now in use or contemplated. These dangerous overvoltages are frequent enough to constitute a real hazard to service, especially in large interconnected systems. They constitute a real barrier to wholly dependable interchange of power and to the economies of load factor, load distribution, best location of steam or hydrogenerating plants which interconnections make possible, since overvoltages causing line flashover seem to be at least as frequent on high-voltage circuits as on low-voltage circuits.

2—At the present time, dependence must be placed on line construction, line insulation, ground wires, etc. to minimize this trouble. In spite of these precautions, some hazard remains.

Voltages as high as ten times normal have been registered, and these can occur only when the wave front is very abrupt, indicating the possibility of still higher voltages if the insulation strength is increased. It appears that the possible overvoltages are beyond the limits of line insulation now used and contemplated. Hence the voltage limit must be considered as that imposed by the line insulation.

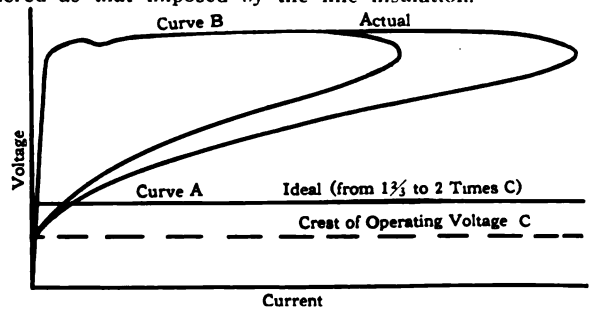


FIG. 3—VOLT-AMPERES RELATION FOR IDEAL AND ACTUAL LIGHTNING ARRESTERS

3—At present it is fairly general practice to use apparatus of less flashover value within the station than on the line. Moreover there are conditions in some stations in which reflections are liable to occur, causing approximately doubling of voltage and causing this increased voltage to be applied first to the station insulation. Flashover in the station under these conditions is likely.

4—Even in the case where station insulation exceeds line insulation in flashover value, and where the relation to the line is such that reflections are not to be expected, flashover within the station might be caused by disturbances originating at the station, when these disturbances give rise to voltages high enough to cause flashover before the effect of adjacent line insulators can come into play. Such flashovers would of course be very infrequent. They are, however, possible.

5—It is to be expected that the life of apparatus insulation is shortened by the repeated application of transient voltages, even though these cause no flashover along the line, and even though they present no hazard of flashover within the station.

6—Service reliability will be improved by the use of effective protective equipment.

## LIGHTNING ARRESTER DESIGN

Reference is made above to the fact that it seems necessary in considering the protection limitations at a station to take into account the kind of operating characteristics present-day arresters afford. This is true because all arresters fall somewhat short of ideal.

The curves of Figs. 3 and 5 illustrate this. Curve *A*, Fig. 3, shows the ideal characteristic. In this curve the voltage is limited to a value slightly above the operating voltage of the circuit throughout the duration of the transient. There is no time lag and there is no rise in voltage with rising current due to impedance in the arrester. Moreover, the voltage does not fall below line voltage at any portion of the transient so that no current will flow due to line voltage. Curve *A* of Fig. 5, illustrates

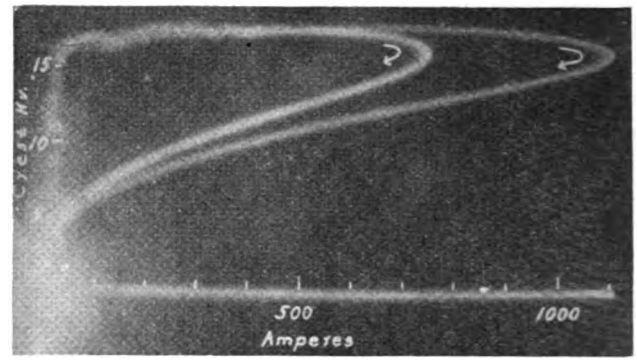


FIG. 4—DU FOUR OSCILLOGRAM OF SURGES WITH DIFFERENT LIMITING VALUES
This is the print from which the curves in Fig. 3 were traced.

the effect of such an arrester on an incident transient, such as is illustrated by curve *C*.

All arresters of present types deviate somewhat from the ideal illustrated above. Curve *B* of Fig. 3 is traced from an oscillogram of a standard Autovalve arrester. It will be noted that the rise in voltage for the increasing part of the transient above the operating voltage value is quite material. The behavior of such an arrester under actual transients on a line is indicated by curve *B*, Fig. 5.

In Fig. 3, the spread between the actual voltages recorded and the ideal curve is a disadvantage. Although efforts are being made to reduce this deviation from ideal, the design considered for actual use in any important proposition has to be based on available and proved principles.

In the proposals for the Conowingo line use was made of standardized units such as shown in Figs. 6 and 7. In these units the operating elements—the columns of discs—are enclosed in a wet process porcelain

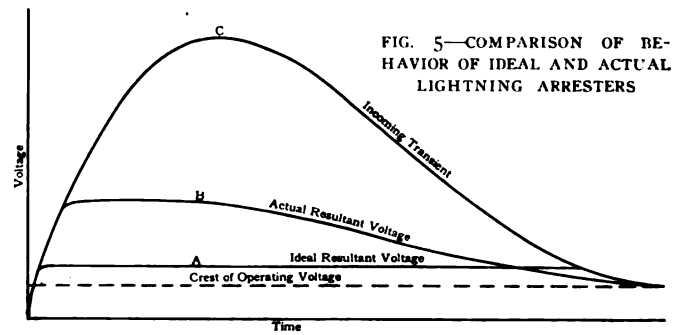


FIG. 5—COMPARISON OF BEHAVIOR OF IDEAL AND ACTUAL LIGHTNING ARRESTERS

housing, fitted with castings for the double purpose of completing the weather-proofing and providing for assembly of the units into a column.

Previous designs for high voltage arresters have used columns which were self-supporting by the inherent strength of the units themselves, as shown

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in Fig. 8. The upper limit of such a construction is seven such units, giving a normal rating of approximately 66 kv. In the case of arresters for high voltages, such as for 140 kv, arrangements were made to support two such columns one above the

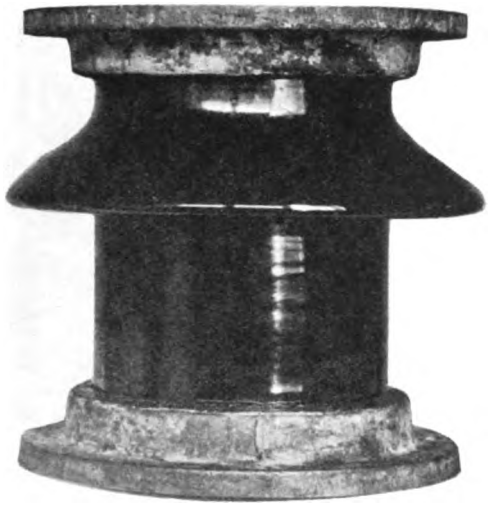

FIG. 6—ONE UNIT OF AN AUTOVALVE LIGHTNING ARRESTER

other as in Fig. 10, so that each would be strong enough to support itself without over-burdening.

If we are to assume, as is the case, that the upper limit for a self-supporting column is seven units (66 kv) it is evident that some other scheme must be arranged for an arrester rated at 220 kv. It would be possible to arrange the design in three columns, but this would have the disadvantage of requiring a considerable addition to the floor space

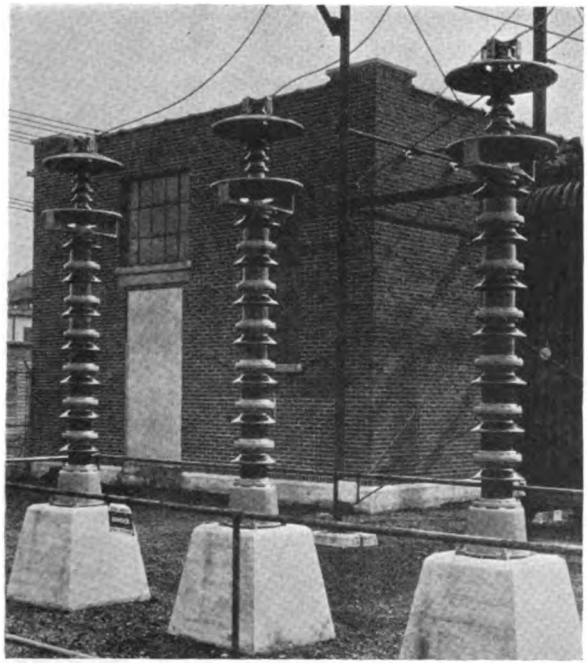

FIG. 8—73 KV LIGHTNING ARRESTERS WITH ENCLOSED GAPS FOR 66 KV SYSTEMS

needed and would require a certain amount of doubling back and forth of the lightning current in the arrester, which might introduce a disadvantage.

After considerable thought, a design was adopted in which the units are arranged in a single column as in Fig. 10. The column would not be sufficiently strong to avoid injury by wind pressure or other side thrust, so additional bracing was supplied by means of tension units. In this structure, the units below the bracing are installed, then the tension members

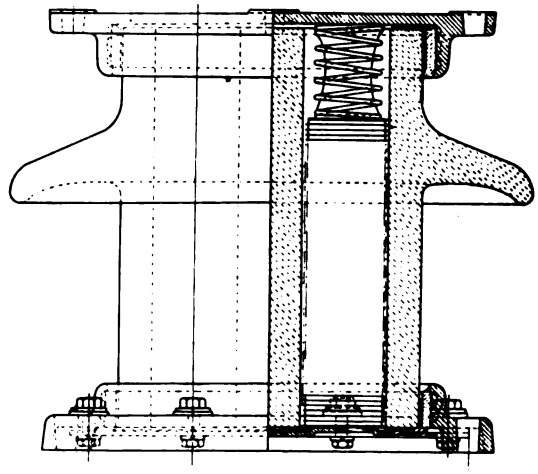

FIG. 7—CROSS-SECTION THROUGH THE UNIT SHOWN IN FIG. 6

are attached to the plate provided for the purpose, and the position of this plate under tension is adjusted to fit the holes through the mounting casting of the upper unit. The upper units are then installed. This provides an exceptionally rugged and rigid structure, occupying relatively small space, as shown in Fig. 11.

### APPLICATION TO A SPECIFIC STATION

Following the procedure normally used to determine designs for specific applications, and basing

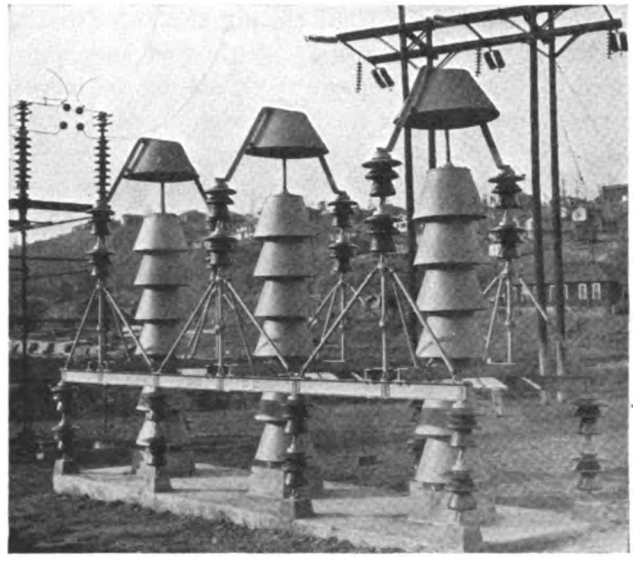

FIG. 9—140 KV AUTOVALVE LIGHTNING ARRESTERS
Each phase leg consists of two columns, independently supported, connected in series.

these designs on principles of construction which have been proved by past experience, the first requirement is to determine the maximum value for operating voltage. In the ordinary case where oper-

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ating conditions are not abnormal, the requirements for this voltage determination are easily met. It is standard practice to provide a factor of safety of approximately ten percent in the arrester element, as in the case of insulation. An arrester for a nominal voltage of 132 kv, for example, will be so designed as to be safe against failure for voltages up to 145 kv. Having established the upper limits of operating voltage, all that is necessary is to select an arrester element whose characteristic curve reaches zero current on the descending part of the wave at a voltage not lower than this upper limit for operating voltage. In this way, the danger of failure to interrupt the current after operation of the arrester is eliminated.

In the case of the Conowingo line there were complications beyond those met in the general case, owing to the possibility of sudden loss of load on a particular generator, causing over speeding and a consequent rise in voltage.

To determine the maximum value to which the operating voltage might rise under such a condition of generator runaway, it was necessary to make a detailed study of the occurrences when load is suddenly lost. The worst condition it is necessary to consider is that of two lines supplied by two generators through two transformer banks, load being dropped by the opening of the high voltage circuit breakers at the receiving end. In this case, the initial rise in voltage is very rapid, due to the generator and transformer regulation plus the rise due to leading line charging current. This initial rise is nearly 40 percent. Following this, the speed of the generator begins to increase, the speed-time curve being determined by the rate of closing the gates and the inertia of the generators. With this increase in speed, the terminal voltage rises, due to the increase in speed and also due to the increase in excitation as the exciter speed is increased. The actual path of the curve depends on the control means provided, which would determine the time of beginning the closing of the gates, and the time of opening the exciter circuits. In Fig. 12 is shown the anticipated voltage with the proposed control means.

This curve indicates the need for providing arresters with a voltage rating of 80 to 90 percent above normal. It is known that the protection given by any arrester to any particular piece of insulation decreases as the rating of the arrester is increased. In the case of the Autovalve arrester, the upper limit of voltage is determined more or less definitely by the arrester, almost without regard for the value of the incoming voltage.

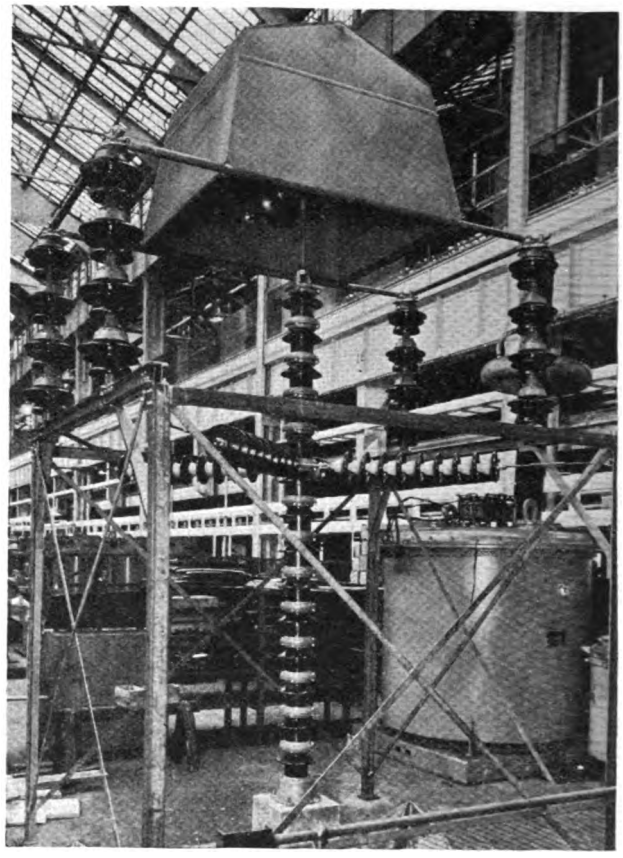

FIG. 10—170 KV AUTOVALVE LIGHTNING ARRESTER BRACED AGAINST SIDE STRAINS

For use on 154 kv systems. The 220 kv arrester is similar to this but has additional units.

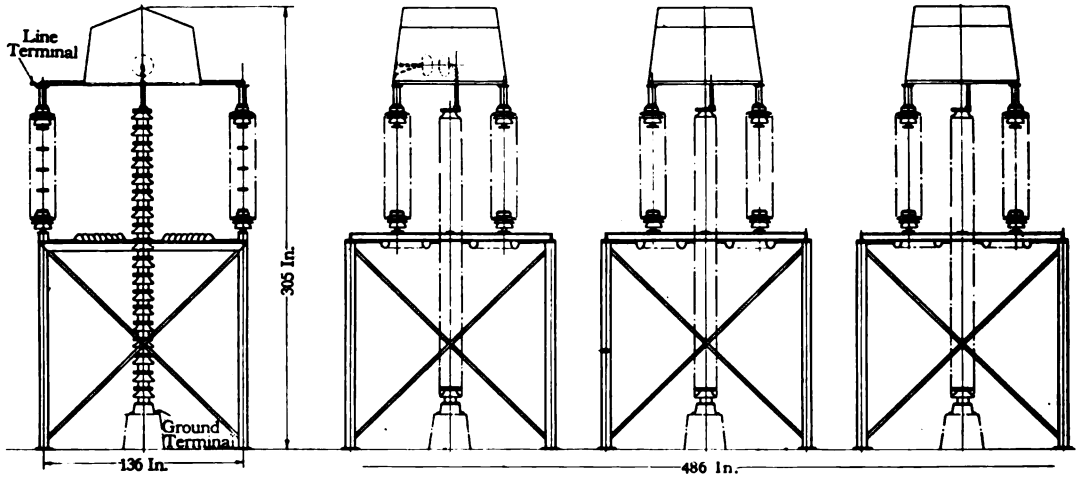


FIG. 11—OUTLINE SKETCH OF A 220 KV THREE-PHASE, AUTOVALVE LIGHTNING ARRESTER

If an arrester for 80 percent overvoltage is pro-

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vided, the voltage which passes the arrester and is impressed on the insulation being protected will be 80 percent above the normal value. Arresters of the types now available do not have a margin of safety of this magnitude to work in. In other words, present-day arresters are not sufficiently good to be able to give satisfactory results with a handicap of 80 percent.

Use is made of the fact that, at the time of generator runaway, it is to be expected that the voltage for the part of the line connected to the generator will be balanced, since whatever fault caused the opening of the circuit breaker, which brought about the overspeeding, will be removed when it is opened.

For all systems which are not solidly grounded at the neutral, lightning arresters are made to provide for full unbalance of voltage between phases, that is, each phase leg is made for full line-to-line voltage. If now the voltage is assumed to be completely balanced, and an arrester is provided with each phase leg, good for line-to-line voltage, a factor of safety of 73 percent is secured against voltage rise. In other words, it is not necessary to provide the full 80 percent increase in voltage rating which is indicated by the voltage curves for the runaway condition. Based on this part of the investigation, and the anticipated switching and control means, decision was reached to provide arresters for just 220 kv for each phase leg.

With the knowledge of the arrester which is to be used, the next step is to determine what voltages may pass the arrester and be impressed on the apparatus insulation. It is planned to construct the transmission line with 14 suspension insulator units. The crest value and 60 cycle flashover for 14 units is approximately 1100 kv. It is known that voltages as high as 2000 kv may be permitted on the line by such insulation, in the case of extremely rapidly rising surges. As indicated above, it is believed that the greater danger is in the longer time voltages with a maximum value of 1100 kv. It must be recognized, however, that the basis of belief that the higher voltages are of extremely short duration, and therefore with small energy content and probably not very dangerous, is not entirely complete. The conclusions may not be correct. Hence the considerations must be based on these higher voltages in order to make the conclusions safe.

The surge assumed for consideration is as indicated in Fig. 13, with a maximum value of 2000 kv, and with a considerable duration. This is considerably more severe than is actually anticipated and provides for a margin of safety to compensate for any errors due to lack of a complete knowledge of the conditions.

Such a surge will cause current in the line of approximately 4000 amperes, assuming a surge impedance of around 500 ohms. The current through the arrester will be of the same order of magnitude. To determine how the arrester behaves under such conditions data should be used based on tests at something like this current value. It is evident that laboratory tests at 2000 kv and several thousand amperes with a duration of a few microseconds are liable to introduce some difficulties. Moreover there are limitations in the possibility of measurements which make such tests still more difficult.

A further difficulty lies in the fact that the conditions in the laboratory, where the characteristics of the circuit are concentrated into a small space, are quite radically different from those in actual service, where the inductance and capacity are distributed along the line. On the line, the duration of the transient is determined by the amount of line charged and the rate of travel of the transient along the line. In the laboratory, the time is affected directly by the rate of current flow. Voltage conditions are also different on the line since, in the laboratory, any energy flowing into the arrester decreases the charge on the laboratory condenser and thus decreases the voltage, while on the line the situation is quite different, in that there is a continuous energy supply flowing into the arrester from the line throughout the duration of the transient.

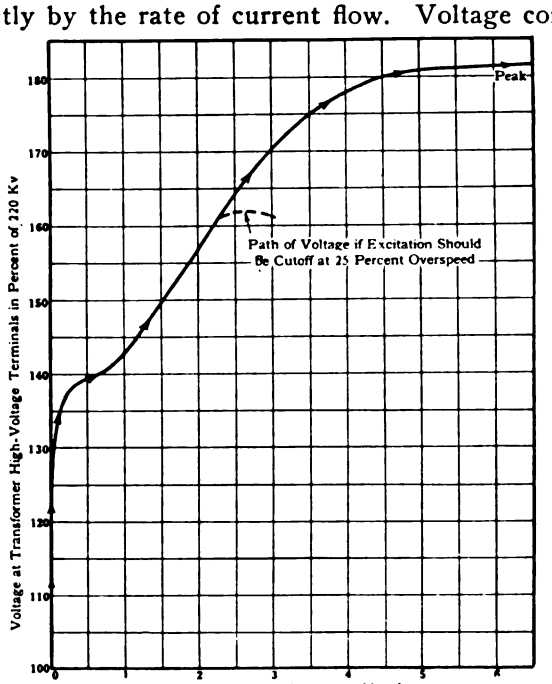


FIG. 12—VOLTAGE-TIME CHARACTERISTICS AT HIGH-VOLTAGE TERMINALS OF TRANSFORMERS

When full load at 90 percent power-factor is dropped from an operating set-up consisting of two lines fed from two generators through two transformer banks, load being dropped by opening the high-voltage circuit breakers at the receiving end.

Several expedients have to be used in order to surmount these difficulties.

1—It is general practice to test arresters of a type which can be readily sectionalized, by testing units or small fractions of complete arresters, and determining the characteristics for the higher voltage assemblies by direct proportionality. There is a good reason to believe that this is a sound practice, since the characteristics are found to be proportional

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to the number of sections in series over the range which can be tested accurately.

2—The most detailed information in regard to transient voltage phenomena can be secured by the use of the cathode ray oscillograph. Thus far, it has not been feasible to make tests at higher than approximately 1000 amperes with this

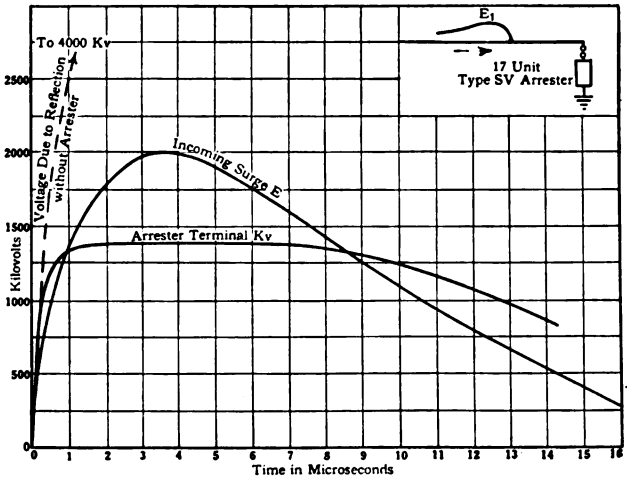


FIG. 13—INCOMING SURGE AND RESULTANT VOLTAGE AT THE ARRESTER TERMINALS

device, on account of the uncertainty introduced by the large stray fields. In this case, it is essential to know how the arrester will behave at currents several times this value. The limitation here is not a lack of the equipment to provide the surge voltages, but in the measuring means. At East Pittsburgh, facilities are available for the provision of unidirectional transient voltages as high as 2000 kv and with an electrostatic capacity of 0.004 microfarads. Circuit characteristics are such as to make it possible to reach currents of 6000 amperes or more, when the impedance added to the circuit is not too great. Detailed information in regard to the behavior of the arrester at currents up to 1000 amperes can be secured with the cathode ray oscillograph, as indicated in Fig. 4. For higher values of current, reliable measurements of crest current and voltage can be secured with sphere gaps. For any particular set of data, the two kinds of tests can be made to overlap so as to provide definite co-ordination between them. Oscillographs can be taken for currents up to 1000 amperes and sphere-gap measurements can be taken for currents from 500 amperes to 4000 amperes. From the two sets of data quite reliable information can be secured as to the behavior of the arrester for all current values up to the highest limit.

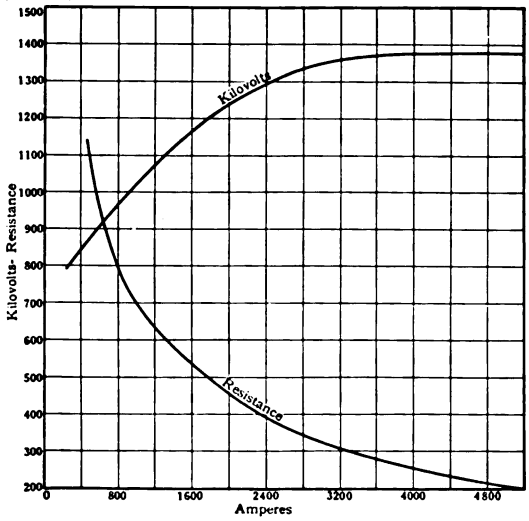


FIG. 14—EQUIVALENT RESISTANCE VALUES FOR A 17 UNIT AUTO-VALVE LIGHTNING ARRESTER

3—To predict the performance on a line from laboratory data, it is necessary to go through a series of calculations. The curves in Fig. 14 are determined from the voltage-current tests just referred to, and indicate the equivalent resistance values for the arrester at various currents. From these values, the actual voltage at the arrester terminals is determined for various points on the assumed incoming transient voltage curve, basing the calculations on an assumed surge impedance of the line. For each point a preliminary determination is made from an assumed value of equivalent impedance of the arrester. If the voltage on the arrester terminal thus determined does not correspond to the assumed value of equivalent impedance of the arrester used in the calculation, a second trial must be made, etc., until the two values correspond. In this way, successive points are determined and a resultant curve of voltage at the arrester terminals as shown in Fig. 13 is established.

It appears clear that this resultant voltage across the arrester terminals is quite safe from the standpoint of flashover of bushings or switches within the station. We must consider the effect on the solid insulation within the transformer to be an unfixed factor. There is probably some damage done, but presumably it is relatively slight.

On the other hand, this station is a terminal for the line. Transients coming in over the line will be reflected at the circuit end and the values approximately doubled by this reflection. For a station which is unprotected, we need consider only the incoming transient, which is of any assumed value, and which approximately doubles when it is reflected at the transformer terminals. If an arrester is to be used, this reflection is prevented, assuming the arrester be placed at the reflection point, namely, at the transformer terminals.

In this particular station, arrangements could not be made to locate the lightning arrester at the transformer terminals and it was necessary to base the considerations on the installation of the arrester at the entrance to the station. Hence, the part of the transient which passes the arrester is transmitted along the station conductors to the reflecting point at the transformer, and approximately doubled in value by reflection. The increased value of the reduced wave persists for the length of time required for the reflected wave to travel from the transformer to the arrester, where it is again reduced, and back again. Some change from these conditions is introduced by the fact that the circuit divides at the bus and that this division brings about a reduction in voltage, owing to the reduction in surge impedance.

It becomes evident that the only way to determine the effect on any assumed incoming transient of all the factors in the station, including the lightning arresters, the division of circuits at the bus, the reflection for a limited period of time, and the second action of the lightning arrester, will be actually to trace out the progress of the transient throughout its duration. Such a study is shown in the various curves of Fig. 15.

At *A* is shown a schematic layout of the station in which the incoming transient first reaches the arrester, then the line circuit breaker, then the bus. At the bus, the circuit divides and goes through two circuit breakers to the transformer terminals.

At *B* is shown the transient, which for convenience in handling is assumed to have a vertical front, just after it has reached the arrester. The transmitted wave with 70 percent of the initial voltage value has passed beyond the arrester, and the reflected wave has traveled back

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an equal distance along the line from the arrester.

At *C* are shown the conditions when the transmitted 70 percent voltage wave has passed the junction at the bus, where the voltage in each direction is reduced to 46.6 percent of the value of the incoming wave.

Further progress is shown at *D*, after the division at the bus in which the reflected wave, reducing the transmitted 70 percent wave to 46.6 percent, has passed by the arrester. Since 46.6 percent is below the operating voltage of the arrester, no influence of the arrester is felt.

The reflection of the 46.6 percent wave at the transformer terminals is shown at *E*, with the reflecting wave travelling back toward the junction between the bus and the line.

The increase in voltage when the reflected wave reaches the junction point is shown at *F*. This increase is to 108.7 percent and the reflected portion of the wave is traveling back toward the transformer.

At *G* the second action of the arrester is shown in reducing the 108.7 percent wave to 70 percent.

A further reflection is shown at *H*, when this 108.7 percent wave reaches the transformer and is again increased to 124.2 percent. At the same time, the effect of the second reduction by the arrester has reached the junction of the bus and the line and gives rise to the 95.8 percent voltage.

The next step is shown at *I*, in which this second reduction by the arrester has influenced the maximum voltage reflected by the transformer.

A further increase in bus voltage is shown at *J* due to the reflection at the junction of the bus and the line, with the maximum voltage at the transformer still remaining unchanged at 124.2 percent.

A reduction at the transformer below maximum is shown at *K* and also a reduction at the bus junction below the maximum value previously reached.

These curves do not in themselves give a very clear picture of the voltage condition at the various times. From them, however, can be drawn curves showing the variation of voltage with time at various points in the station. Such curves are shown in Fig. 16 for the point where the line joins the bus and for the transformer terminal.

If the insulation strength of the yard apparatus is assumed to be the same as for the line, and if the surge being investigated is assumed to be the maximum one which will not cause flashover along the line, so that any increase in either voltage or time of duration of the surge would cause a flashover, then any increase in voltage of the surge within the station beyond 100 percent of the incoming value will cause flashover within the station, no matter how short is the time during which this increased value exists. On these assumptions then, it is to be expected that flashover will take place not only at the transformer terminals, but also at the junction between the bus and the line, since at both these points the surge voltage rises above the 100 percent value.

As has been pointed out earlier, there is not sufficient information to get a definite evaluation of the possible effect of these extra voltage values on the insulation within the transformer. It seems quite clear however that the values are sufficiently high that a dangerous effect might be produced. As stated above, the 70 percent value to which the arrester initially re-

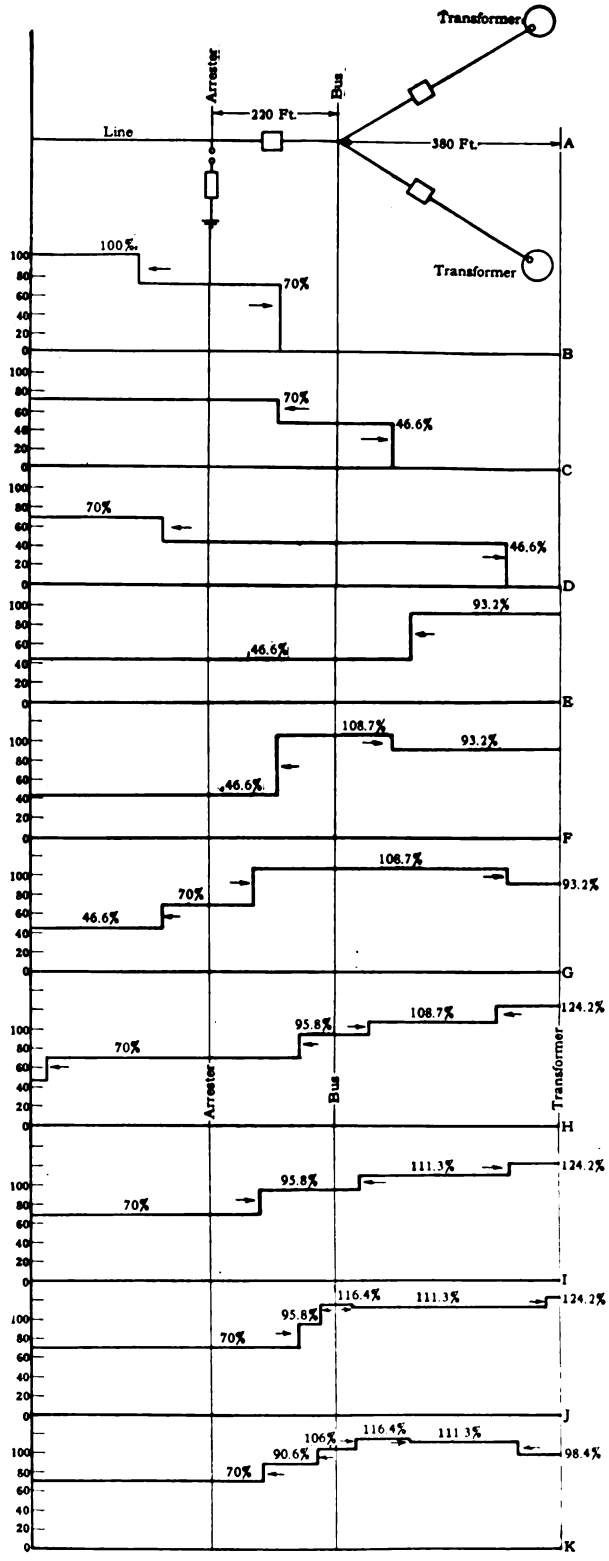


FIG. 15—SURGE STUDY FOR THE CONDITIONS IN THE CONOWINGO STATION

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duces the incoming voltage will probably cause a certain amount of deterioration, but this is felt to be small. The ultimate value to which this voltage will finally settle down will be the 70 percent value. During the initial part of the transient, however, while the reflections between the arrester and the transformer are taking place, the voltage rises noticeably beyond the 70 percent value and, since the damage done almost certainly increases rapidly with increasing voltage, this may radically in-

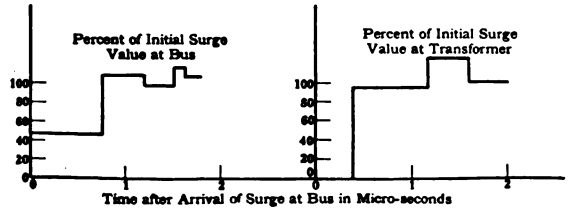


FIG. 16—SUMMARY OF SURGE STUDIES

crease the amount of the damage done the transformer insulation. From Fig. 16 it is evident that, for the first two microseconds, the value is only slightly less than 100 percent at any time and for a period of nearly one-half microsecond it rises to 125 percent.

There is some advantage to be expected in reducing these short-time excess voltages by the effect of the capacity within the station. This is particularly true when transformer bushings and circuit breaker bushings are of the condenser type, in that a considerable amount of energy can be stored in these capacities, which brings about a reduction in the actual potential until these capacities are charged. Since these durations are rather long, however, the effect of the various capacities may be nearly disregarded in this particular case.

The fact that energy storage devices may be useful in caring for the short-time overvoltages discussed above suggests the desirability of an investigation as to the possibility of eliminating these overvoltages by the use of choke coils. Care must be used, however, to make sure that the use of choke coils does not introduce conditions causing higher voltages than would exist without these coils. The transient entering the station may be considered as encountering a circuit composed of the choke coil and connected capacities, as indicated in Fig. 17. If the relations of this circuit are such that the surge impedance does not provide critical damping for the resonant circuit composed of the choke coil

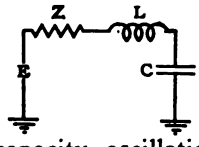


FIG 17—SCHEMATIC DIAGRAM OF CIRCUITS ON WHICH AN INCOMING SURGE IS IMPOSED

and capacity, oscillations such as shown in Fig. 18 may be anticipated. If, on the other hand, the surge impedance of the line is sufficient to cause the charging of the capacities through the inductance to be aperiodic, the oscillations will be prevented and the voltage will rise to its final form as indicated in Fig. 19.

From this standpoint, for any particular condition, the maximum safe size for the coil will be that defined by the relation $Z = 2\sqrt{L/C}$. The limiting condition is for the minimum connected capacity; that is, when a line circuit breaker is open and a single bushing is connected. Any other condition will have greater capacity and therefore be safer.

From the standpoint of effectiveness in reducing the short time over-voltages at the beginning of a transient, as large inductance as possible is needed. Some idea of the effectiveness of the coil can be gotten by considering the time constant, and the assumption is made that it would be desirable to have a time constant of the order of one microsecond in order safely to take care of the one-half microsecond dangerous overvoltage condition, with a little margin to assist in reducing the longer over-voltage which is probably dangerous to the transformer insulation, although it might not cause flashover. Such a coil would have an inductance of approximately 0.25 millihenries.

The maximum coil which it will be safe to use with the limiting condition of the line circuit breaker being open will have an inductance of 0.025 millihenries, or about one-tenth that necessary to give the desirable time constant.

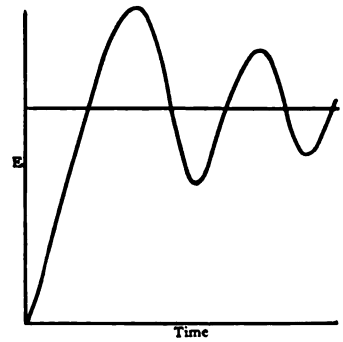


FIG. 18—TYPICAL OSCILLATORY CASE

Two alternative expedients may be proposed to take care of the situtation. First it is possible to use a coil of approximately 0.025 millihenries in the line ahead of the initial circuit breaker. This can be supplemented by a second coil connected between this circuit breaker and the bus, and this coil may safely have an impedance of 0.13 millihenries. The use of these two coils together will give something like 60 percent of the value indicated as desirable, and since this desirable value is rather indefinite, it may be assumed that this is a feasible recommendation.

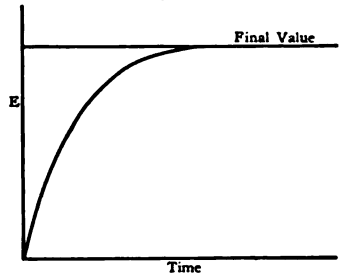


FIG. 19—APERIODIC CASE

The second alternative would be to use a coil of the size necessary for the desirable time constant and prevent troubles due to oscillations by shunting the coil with a suitable resistor. Such a coil will be considerably larger and more expensive, both to build and to install, than the combination of two coils and the decision between them is largely one of economics.

## RESUME

To determine the benefits to be secured by protection at this station, consideration was given to the proposed line insulation, station yard insulation and apparatus insulation. Assumptions were made as to the most severe transient which is likely to occur on the

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line. The proper arrester was selected to suit the anticipated operating voltage conditions. From the characteristics of the arrester and line and from the station layout, determinations were made of the voltage which will be applied to the station equipment when such a maximum transient arrives at the station. It was found that these voltages may be dangerous but that special choke coils will reduce and may be expected to eliminate this danger.

It is to be kept in mind that the conditions in this case are somewhat special, and that deviations from usual construction practice in smaller stations are such as to make the protection problem abnormally difficult. In the first place, it is necessary to use an arrester of rather higher than normal rating, thus making the voltages incident to the apparatus greater than would ordinarily be the case. In the second case, the distance between the transformer and the arrester is abnormally long, so that the time for the multiple reflection condition is far longer than ordinarily. It is not possible to protect two widely-separated points with a single lightning arrester. The best that can be done is a compromise and the farther apart the two points under consideration are, the more the difficulty. Where the point at which the arrester must be connected is 700 feet away from the point of reflection, the difficulty is considerable.

On the other hand, the conclusions from this study indicate that there are probably other cases in which such a study would point out hazards both to yard flashover and apparatus damage which might be avoided by some relatively minor changes in the protection scheme. Such studies will probably be found to be well worth while in other installations.

# Electrical Insulating Oil (Concl.*)

DEAN HARVEY

## TEST METHOD

*Method of Test for Dielectric Strength*—On account of the very great sensitivity of insulating oil to water and other impurities, the greatest care is necessary in making the dielectric test to avoid contamination of the sample. It is important that the method be followed in every detail as outlined below in order to insure reliable results. This method is based on the recommendations of the American Society for Testing Materials and represents safe practice.

*Apparatus*—The transformer and the source of supply of energy shall not be less than 0.5 kv-a, and the frequency shall not exceed one hundred cycles per second. Regulation should be so controlled that the high-tension testing voltage

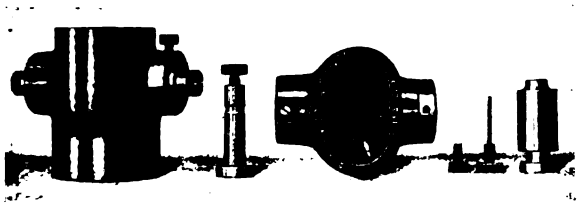

FIG. 4—OIL TEST CUP ASSEMBLED AND UNASSEMBLED

taken from the secondary of the testing transformer can be raised gradually, at the rate of approximately 3000 volts per second, without opening either primary or secondary circuit. This is important, as any opening of the circuit will introduce a momentary voltage rise which may be sufficient to cause breakdown of the oil, thus giving an unduly low value for its dielectric strength. The voltage may be measured by any approved method which gives root-mean-square values.

Some protection is desirable to prevent excessive flow of current when breakdown of the oil takes place. This protection preferably should be in the low voltage side of the testing transformer. It is not especially important for transformers of 5 kv-a or less, as the current is limited by the regulation of the transformer.

The test cup for holding the sample of oil must be made of a material having a suitable dielectric strength. It must be insoluble in and unattacked by mineral oil and gasoline and non-absorbent so far as moisture, mineral oil and gasoline are concerned.

The electrodes in the test cup between which the sample is tested are circular discs of polished brass or copper, one inch in diameter and having square edges. The electrodes are mounted in the test cup on the same horizontal axis, with a gap of 0.100 in. between their adjacent faces, and with the top of the electrodes about 1.25 in. below the top of the cup. A suitable test cup* is shown in Fig. 4 and portable testing outfits in Figs. 5, 6 and 7.

*Procedure*—

*a*—The electrodes and the test cup should be wiped clean with dry calendered tissue paper or with a clean, dry chamois

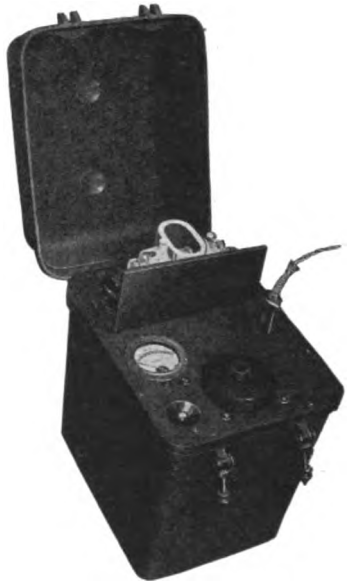

FIG. 5—A PORTABLE, 25 000 VOLT OIL TESTING SET

skin, and thoroughly rinsed with oil-free, dry gasoline or benzine until they are entirely free from fibers. A moist

*Continued from February, 1928, p. 99.

*Other forms of test gaps now in use are: (1) metal discs 0.5 in. in diameter spaced 0.2 in. apart with their axes horizontal, and (2) spheres 1/2 in. in diameter spaced 0.15 in. apart with the axis of the gap vertical. If the values of dielectric strength observed with gaps of these two types are multiplied by the factors 0.55 and 0.50 respectively, the results will give the dielectric strength of the oil in the standard gap of 1 inch disc spaced 0.100 in. apart.

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or contaminated test cup is a frequent cause of erroneous test results.

*b*—The spacing of electrodes should be checked with a standard round gage having a diameter of 0.100 in. and the electrodes then locked in position. Care shall be taken not to touch the electrodes with the gauge, or in any other manner, after cleansing the electrodes and cup, so as to avoid any possible contamination.

*c*—The test cup is filled with dry gasoline or benzine, and voltage applied with uniform increase at the rate of approximately 3000 r.m.s. volts per second until breakdown occurs. If the dielectric strength is not less than 25 kv., the cup is to be considered in suitable condition for testing the oil. If a lower test value is obtained the cup should be cleaned with gasoline and the test repeated.

Evaporation of gasoline from the electrodes may chill them sufficiently to cause moisture to condense on their surfaces. For this reason, after the final rinsing with gasoline, the test cup should be immediately filled with the oil which is being tested and the test proceeded with at once, or else the electrodes should be thoroughly dried.

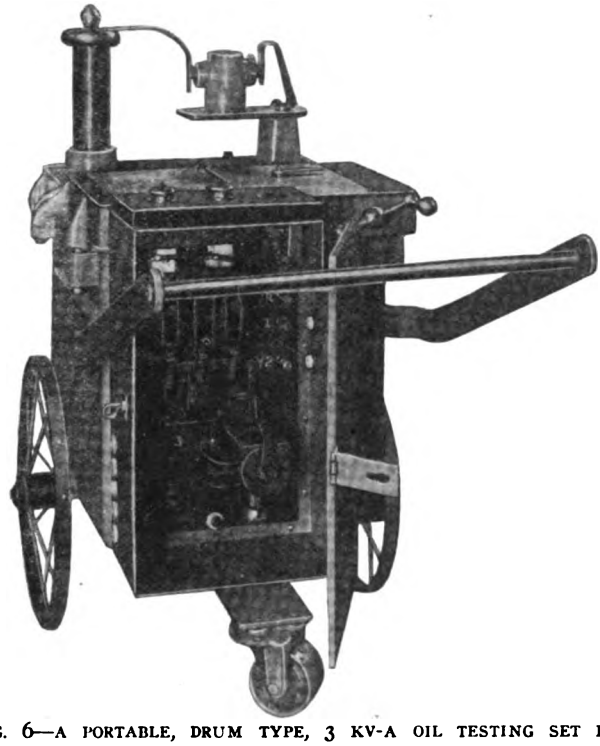

FIG. 6—A PORTABLE, DRUM TYPE, 3 KV-A OIL TESTING SET FOR 30 000 VOLTS

*d*—The temperature of the test cup and of the oil when tested should be the same as that of the room, which should be between 20 and 30 degrees C. (68 and 86 degrees F.). Testing at lower temperatures is likely to give variable results which may be misleading.

*e*—The sample in the container should be agitated with a swirling motion, to avoid introducing air, so as to mix the oil thoroughly before filling the test cup. This is even more important with used oil than with new oil, as the impurities may settle to the bottom and the test be misleading.

*f*—The cup is filled with oil to a height of not less than 0.79 in. (20 mm) above the top of the electrodes.

*g*—The oil should be gently agitated by rocking the cup, and then allowed to stand in the cup for three minutes before the first, and one minute before each succeeding puncture. This will allow air bubbles to escape. Air bubbles in the oil are a common cause of low and variable test results.

*h*—Voltage is applied and increased uniformly at a rate of approximately 3000 r.m.s. volts per second until breakdown occurs, as indicated by a continuous discharge across the gap. Occasional momentary discharges which do not result in a permanent arc may occur; these should be disregarded.

*i*—Provision should be made for opening the circuit as promptly as possible after breakdown has occurred, in order to prevent unnecessary carbonization of the oil. After each puncture, the testing vessel should be jarred to loosen particles of carbon adhering to the electrode, and the oil gently agitated but not with sufficient violence to introduce air bubbles.

*j*—Five breakdowns are made on each filling, after which the vessel is emptied and refilled with fresh oil from the original sample. The test is continued until the averaged values of at least three fillings do not differ from their mean by more than 10 percent.

*Report*—The report should include the volts (r.m.s. value) at each puncture, the average voltage for each of the three or more fillings, grand average voltage and the approximate temperature of the oil at the time of the test. The diameter of disc electrodes and the gap should also be given.

A precision of about three percent may reasonably be expected in 15 tests distributed among three consistent fillings taken in succession. But if the length of the gap is readjusted and possibilities of contamination exist, the precision may be only 6 or 7 percent. Differences as great as 10 or 12 percent may occur between different laboratories, even where the work is carefully done.

## PURIFICATION

The purification of used oil from circuit breakers and transformers as now carried on consists principally in the removal of water, carbon and sludge and sometimes in the restoration of its resistance to emulsification.

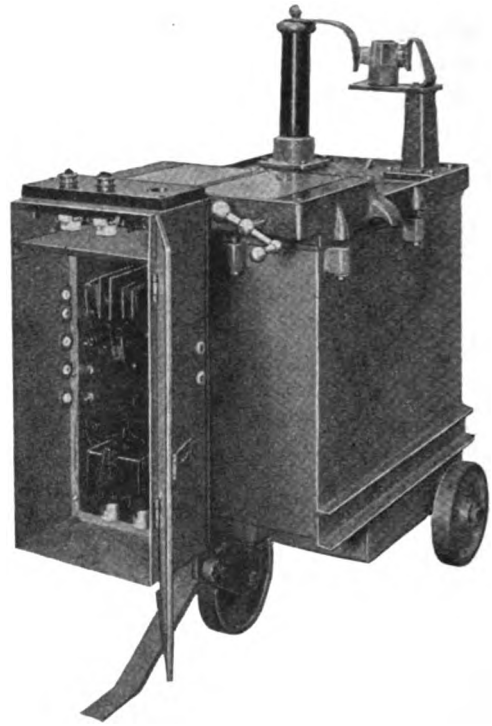

FIG. 7—A PORTABLE, DRUM TYPE, 10 KV-A OIL AND INSULATION TESTING SET

Two types of equipment for purification of oil are in general use, the centrifuge and the blotter filter press. The best and quickest method of purifying oil is to pump all the oil from the tank through the centrifuge or filter press and into another tank which is dry and clean. Oil in transformers contaminated by only a small amount of water may be purified by drawing the oil from the bottom of the tank, passing it through the centrifuge or filter press and pumping it back into the transformer tank, preferably at a point below the oil level. The oil is put through the system until a sample drawn from the bottom of the transformer shows satisfactory dielectric strength.

Pumping sludged oil from a transformer tank, or carbonized oil from a circuit breaker tank, through the purifying outfit and directly back to the tank is not desirable, as the clean oil is again contaminated by the dirty oil remaining in the tank. Also this does not

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allow the deposit of sludge or carbon to be removed from the tank and from the windings and other parts of the apparatus.

*Blotter Filter Press*—The filter press is essentially a number of sets of filter paper in parallel, each set containing several thicknesses. The oil is pumped through the filter paper, which absorbs the water and strains out the sediment. A typical filter press is shown in Fig. 10. The complete outfit consists of filter press, oven for drying the filter paper, motor, pump, oil strainer, pressure gage and piping.

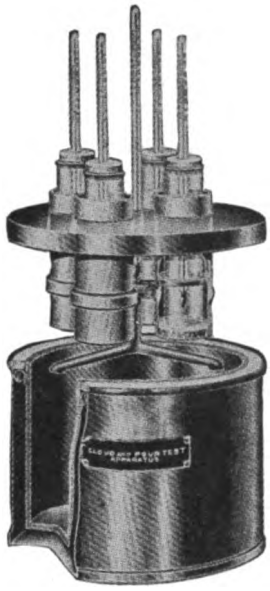

FIG. 8—APPARATUS FOR POUR TEST

The filter press is not intended to remove large amounts of water from the oil. Obviously the changing of filter papers necessary for obtaining dry oil under such conditions would so reduce the capacity as to make this method of purification impracticable. In such cases the water may be removed by a centrifuge, or it should be allowed to settle out and be drawn off from the bottom of the container before passing the oil through a filter press.

When the oil contains only a small amount of water, carbon or sludge, the sediment and water can be removed by passing the oil once through the outfit. If any water remains after filtering, it indicates that the filter papers are saturated with water and must be removed. With badly fouled oil, it may be necessary to pass the oil several times through the filter press to take out the more finely divided carbon which is not caught in the blotters, especially when they are new. The efficiency of the filter press for removing carbon increases as the blotters become partly clogged, but this considerably slows down the rate of flow through the blotters.

Filtering through blotters does not materially reduce organic acidity or improve resistance to emulsification, except as the latter is affected by the presence of carbon, although the dielectric strength may be restored to a satisfactory value. The oil may be filtered without first heating it, but the capacity of the filter press is much reduced at low temperatures. When the oil has to be lifted at low temperatures, an additional pump in the pipe line is desirable.

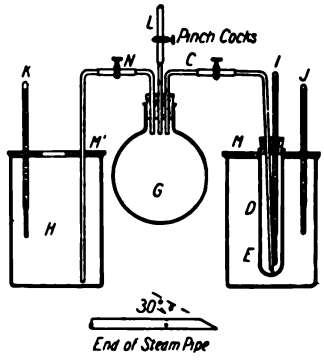


FIG. 9—APPARATUS FOR RESISTANCE TO EMULSIFICATION TEST

*The Centrifuge* is the most convenient equipment known for removing water from oil. It also removes solid impurities other than finely divided carbon. A portable centrifuge is shown in Fig. 11. The temperature of the oil should be maintained at 49 to 52 degrees C (120 to 125 degrees F.), by means of an electric heater, in order to insure removal of all the water at full capacity of the machine. A higher temperature gives no advantage and if excessive, is harmful to the oil. A 6 kw heater will raise the oil about 33 degrees C (60 degrees F.) per 100 gallons per hour. The centrifuge equipment may be arranged to act as a separator, discharging the oil and water by different outlets, or as a clarifier, discharging the oil, but retaining in the bowl the water and other impurities. When there is considerable water in the oil, it should be operated as a separator. The necessity of this will be apparent by the quantity of water coming from the outlet. If only a small amount of water appears through the water outlet, a larger output may be obtained by operating as a clarifier, in which case the water is retained in the bowl. Generally only small quantities of water

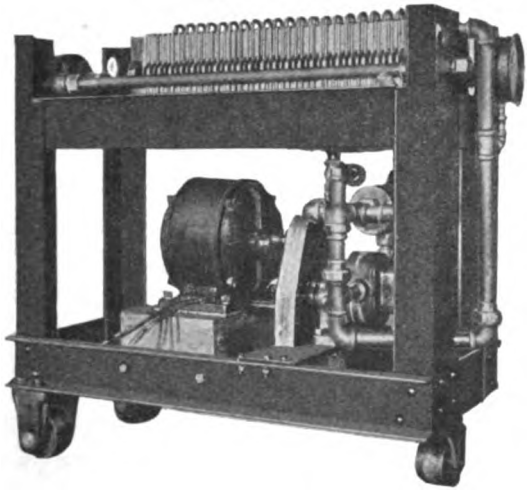

FIG. 10—AN OIL FILTER PRESS

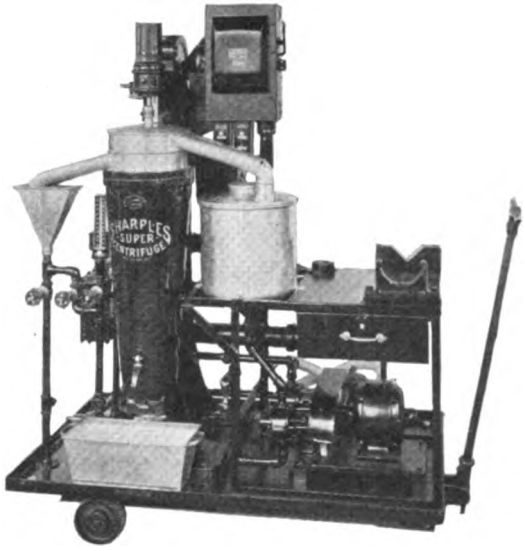


FIG. 11—A PORTABLE CENTRIFUGE

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are present and the equipment is used as a clarifier. When operating as a clarifier the bowl should be changed at intervals, in order to insure dry oil, and avoid contamination through wet oil passing into the purified oil container.

One manufacturer has developed a combination of the centrifuge with a chemical treatment of the oil, which is particularly applicable to circuit breaker oil. By this means the water and carbon are removed, the resistance to emulsification is restored and the organic acidity is reduced to a low value.

The dirty oil is introduced into a mixing tank where it is heated to a temperature of about 52 degrees C. (125 degrees F.) and maintained at this temperature through the operation. It is then mixed with a weak aqueous alkali solution and stirred for a sufficient time to insure a thorough mixing with the reagent. The presence of the alkali facilitates the dispersion of the solution through the oil, forming a weak emulsion. The alkali acts upon each particle and facilitates its removal by the centrifuge. The alkali also neutralizes any organic acids present and also acts upon other oxidation products formed by the deterioration of the oil, thus restoring its resistance to emulsification. The mixture is then passed through a centrifuge operating as a separator, which removes the water and alkali with nearly all of the impurities.

The oil next is pumped to a second mixing tank where it is thoroughly stirred with water and fine clay until it has been thoroughly washed and cleaned. The clay has a scouring action on the oil, taking hold of the last traces of impurities. A second centrifuge operating as a clarifier removes the water, clay and impurities, discharging oil which is brilliant, clean and dry.

With this process the oil may either be run continuously or in batches. There is a wide difference in the results obtained with different grades of the reagents used, and it is therefore necessary to select them so that they will accomplish the desired result without producing harmful compounds in the oil. The arrangement of equipment is shown in Fig. 12. Chemical treatment of oil should only be done with the approval of the manufacturers of the apparatus in which the oil is used. Chemical treatment of oil from transformers is still in the experimental stage.

### COMPARISON OF PURIFYING PROCESSES

The centrifuge connected as a separator may be used when large quantities of water are present in the oil without waiting for it to settle out, and connected as a clarifier for removing small quantities of water. It will remove sludge and course carbon particles, but not all finely divided carbon.

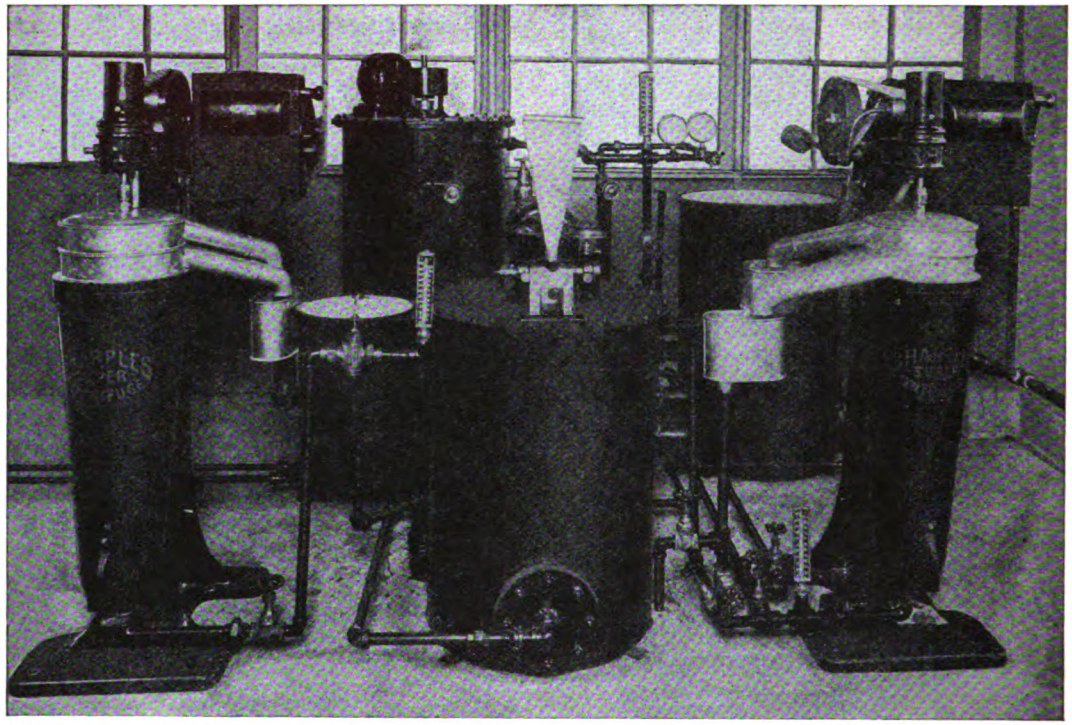

FIG. 12—OIL RECLAIMING EQUIPMENT FOR CIRCUIT BREAKER OIL
This combines the centrifuge and chemical treatments.

The filter press is suitable for purifying oil containing small quantities of water and will remove finely divided carbon and sludge. It will not materially improve the resistance to emulsification, except as this is caused by the presence of carbon, and it will not materially reduce the organic acidity.

A combination of the centrifuge and filter press is sometimes used, with advantage as indicated under the two kinds of apparatus.

Suitable chemical treatment in conjunction with the centrifuge will remove water and carbon from circuit breaker oil, also restoring the resistance to emulsification and reducing the organic acidity.

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# Recent Developments in Current-Limiting Reactors

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RECENT developments in current-limiting reactors have followed two general lines—improvements in dry-type reactors for low-voltage and indoor application, and the development of oil-immersed reactors for high-voltage and outdoor applications.

### DRY-TYPE REACTORS

It has become recognized as desirable to insulate the individual conductors of reactors in order to remove the danger of failure due to stray magnetic material being drawn into the reactor at times of short-circuit. It appears that, in spite of the most careful scrutiny and attention, foreign magnetic material sometimes is found around the floor near a reactor installation and is drawn into the reactors, causing their failure. Undoubtedly some of the early failures in reactors which were unexplained at the time may be attributed to this cause. Statistics also indicate that a large proportion of reactor failures have been due to insulation troubles[1].

### INSULATED COVERING FOR REACTOR CABLES

Two types of insulated coverings are suitable for use on dry-type current-limiting reactor cables—Class A or Class B[2]. In the development of suitable materials for the purpose, it was found that the best Class B materials available, although they would permit higher temperature operation, were not as suitable as certain Class A materials.

The Class A insulation developed for the purpose is made by running the cable through a trough of bakelite varnish and applying cotton tape, half-overlapped. After winding, the coil is dipped in bakelite varnish and then in black insulating varnish. By this means a simple, durable, moisture and heat-resisting, strong insulation of high dielectric strength is obtained.

The best Class B insulating materials are composed of asbestos coverings which of necessity contain fibrous or Class A binders and are impregnated with certain paints or compounds to make the asbestos less moisture absorbent.

A reactor must be able to carry its rated current continuously without overheating, and must be able to withstand the thermal effects of currents which may flow during periods of short-circuit. The proposed revised A.I.E.E. rules[3] have established 55 degrees C. as the normal temperature rise for class A insulated reactors, and 80 degrees C. for Class B insulators; with an ultimate temperature rise under short-circuit conditions of 250 degrees C. for Class A, and 350 degrees C. for Class B. These latter temperatures are calculated temperatures, based on the assumption that all the heat generated is stored in the copper during the period of short-circuit. The actual copper temperatures are much less than these calculated temperatures.

It becomes, therefore, a matter of design to provide sufficient copper, so that the required temperature rises are not exceeded when either class of insulation is used under the given conditions. Under abnormal conditions of operation at the time of short-circuit, the limit of operation for either type of insulation is the smoking temperature. Smoke is objectionable in the reactor vaults for obvious reasons.

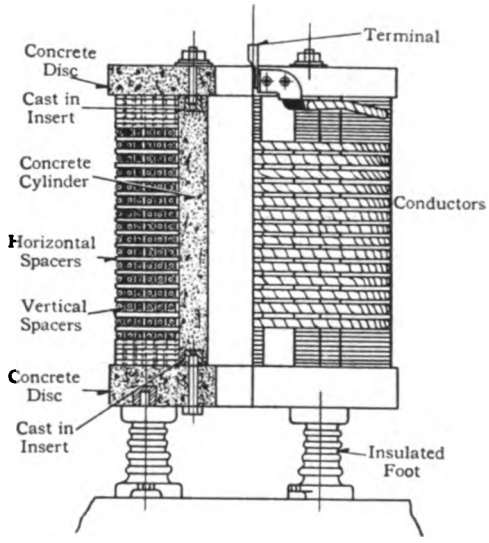


FIG. 1—CONSTRUCTION OF A DRY-TYPE REACTOR

It has been found that with the Class A insulation described, the smoking temperature is very close to that of the Class B insulation described. The average smoking temperature found in a series of tests with the Class A insulation is about 175 degrees copper temperature as measured by thermocouples attached to the metal. The equivalent calculated temperature based on all heat stored is 288 degrees C., so that the temperatures obtained with conductors designed in line with the proposed A.I.E.E. limit of 250 degrees C. will be well below the actual smoking temperature. In another series of tests with the Class B insulation, smoking started at 200 degrees C., or only 25 degrees C. higher, with the equivalent calculated temperature of 332 degrees C. For the required conditions of design, the Class A material used has, therefore, much greater thermal advantage than the Class B material. In other

[1] N.E.L.A. Electrical Apparatus Committee Report, 1926.
[2] A.I.E.E. Standardization Rules, Par. 13-202, Par. 13-203.
[3] See A.I.E.E. Standardization Rules, Par. 13-200, 13-250, 13-252, and A.I.E.E. Journal, August 1927, p. 845.

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words, a reactor designed on the basis of all heat stored in accordance with the proposed A.I.E.E. rules will have a greater margin of safety between actual temperatures and smoking temperatures when Class A insulation is used than when Class B insulation is used.

Class A material is naturally a much better insulator than the asbestos material. The ratio of dielectric strength for Class A cable as described, and Class B cable with a covering of asbestos fifty mils thick, is between two and three to one.

### A NEW REACTOR STRUCTURE

This new fibrous, heat-resisting insulated cable forms the basis of a new reactor structure of unusually high dielectric and mechanical strength. The basis structure, Fig. 1, consists of a concrete spool, comprising a cylinder to which are bolted a top and lower concrete disk, which are provided with holes for ventilation. Inserts cast into the cylinder are used to bolt the cylinder to the top and bottom disks without the use of metallic bolts extending from top to bottom of the reactor, this being objectionable from an insulation point of view.

The reactor coil consists of a helical winding wound from the center out and from the outside in on alternate layers. Each layer is separated by horizontal cleats, and each turn is separated by a vertical spacer which passes through slots in the cleats. In winding, the vertical spaces are entered in the lower layers of horizontal spacers and are progressively pushed up through the horizontal cleats, Fig. 2, as the cable is

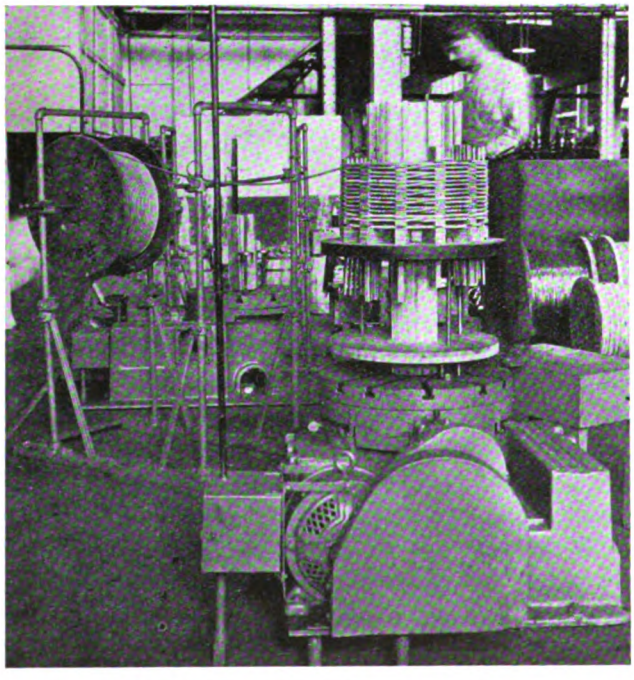

FIG. 2—WINDING A DRY-TYPE REACTOR

wound. Fig. 3 illustrates the winding construction more in detail.

The completed coil is impregnated first in bakelite varnish and finally in black insulating varnish, so that a rigid solid mass is obtained. The ends of the windings are rigidly bolted to terminals attached to inserts in the concrete disks, as indicated in the complete reactor, Fig. 4. The insulating feet also screw into inserts

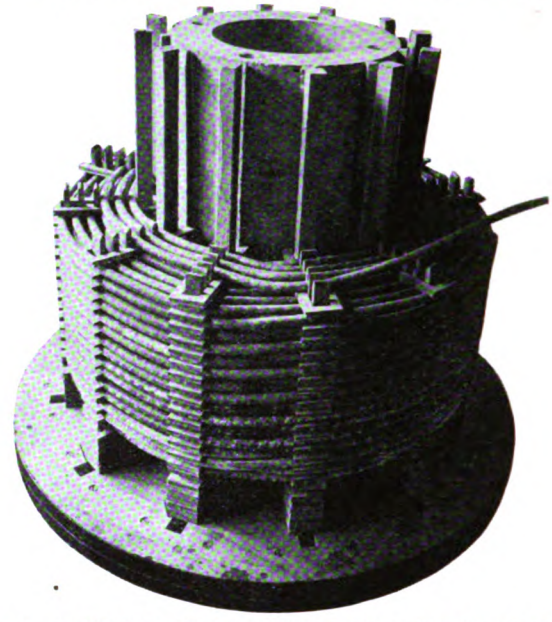

FIG. 3—A CLOSE UP OF THE REACTOR BEING WOUND IN FIG. 2

in the bottom disk. The reactor may be lifted and handled as a unit by using a sling through the center hole, engaged with a wooden cross-piece, Fig. 5.

This reactor construction has been subjected to repeated and sustained short-circuits. The results of tests on a typical unit, are given in Table I. These tests are far more severe than those likely to be encountered under service conditions.

In several of the tests, nails and other magnetic

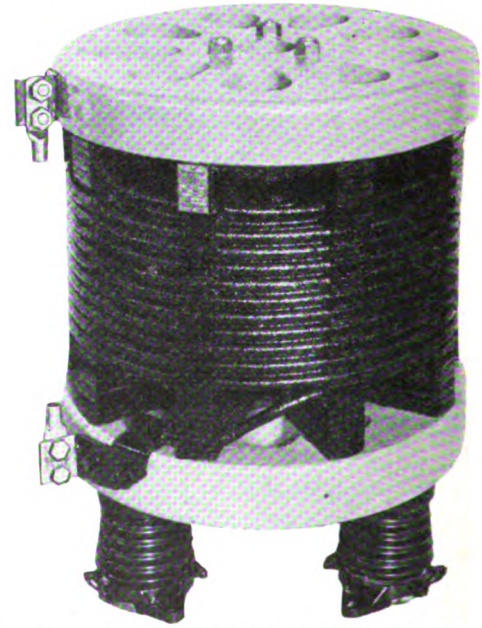

FIG. 4—A COMPLETED DRY-TYPE REACTOR
This reactor is rated at 18.4 kv-a at 200 amperes and has 4 percent reactance on a 4000 volt line.

materials were placed near the reactor and were drawn in when the short-circuit was applied. In no case was the slightest evidence of damage noticed. Slow motion

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pictures were taken of these tests, in which the progress of one of the nails may be traced step by step.

Dry-type reactors are suitable for voltages up to 15 000 volts. For use above this voltage the oil immersed current-limiting reactor has been developed.

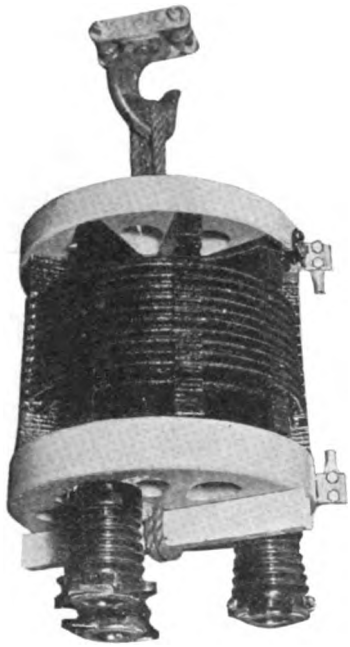

FIG. 5—LIFTING THE COMPLETED REACTOR

OIL-IMMERSED CURRENT-LIMITING REACTORS

The development of an oil-immersed reactor consists largely of devising means for shielding the enclosing case from the effects of the reactor magnetic field. If a reactance coil is placed in an ordinary steel tank, the hysteresis and eddy-current and other stray losses in the tank due to the extensive stray magnetic field become very high, giving objectional loss and heating in the tank. If non-magnetic tank material is used, the hysteresis loss is eliminated, but the eddy-current loss becomes excessive due to the lower electrical resistance.

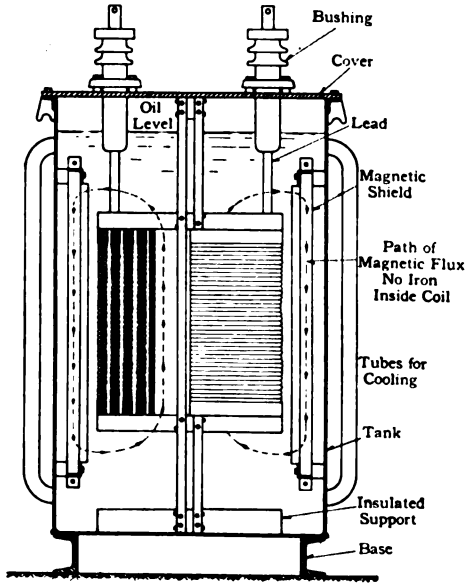


FIG. 6—A SCHEMATIC DIAGRAM OF AN OIL IMMERSED REACTOR
Showing the method of shielding and the winding arrangement used in reactors shown in Figs. 7, 8 and 9.

The low-resistance, short-circuited turn formed by the tank wall is also objectional, on account of the current induced in it by transformer action, which introduces still more loss.

The obvious thing is a tank of non-magnetic and non-metallic construction, something which is not at present practicable for an oil-container or a heat dissipater; or as a compromise a metal of very high resistance and low permeability. Metals meeting these requirements are available, but they must either be used in the cast form and hence are not suitable for the fabrication of large oil-tight tanks, or they are expensive alloys, not suitable for economical reasons.

TABLE I—SHORT-CIRCUIT TESTS ON AN 18KV-A, 200 AMPERE REACTOR
Reactance, 3.75 percent on a 4160 volt line.

| Amperes | | | Volts | | |
|---|---|---|---|---|---|
| Initial Maximum | 1st cycle r. m. s. | Final r. m. s. | Initial r. m. s. | Final r. m. s. | Time in Seconds |
| 10 200 | 6060 | 3180 | 2920 | 1670 | 2.82 |
| 11 200 | 6750 | 3540 | 2920 | 1875 | 1.77 |
| 14 300 | 8400 | 3540 | 2920 | 1795 | 2.7 |
| 15 000 | 8900 | 3540 | 3000 | 1850 | 2.14 |
| 13 700 | 8200 | 3420 | 2560 | 1650 | 5. |
| 14 850 | 8925 | 5190 | 2880 | 2525 | 42. |
| 4 580 | 2875 | 2820 | 1250 | 1170 | 22.3 |
| 8 960 | 5760 | 3975 | 2060 | 1840 | 6.22 |
| 9 250 | 5170 | 4465 | 2400 | 1980 | . . |

The problem has been solved with the ordinary steel tank construction used with transformers, by providing inside the tank a high permeability shunting path of laminated steel for the return path of the reactor leakage flux. Fig. 6 illustrates such a construction in cross-section. The leakage path, instead of being through the tank wall, is through the laminations as indicated. Sufficient high-grade steel, such as is used for transformer cores, is used to keep the flux-density low, so that the loss in this shield is quite low. Sections of punchings are shown in Fig. 7 secured in frames which are bolted to the tank wall.

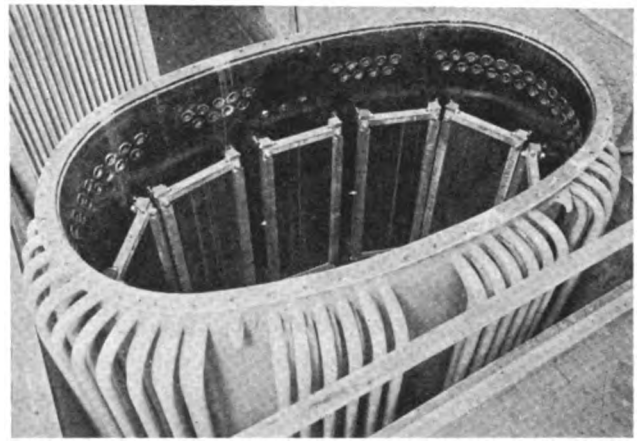

FIG. 7—LOOKING INTO THE TANK OF A LARGE OIL-IMMERSED REACTOR
Showing the magnetic shields lining the tank walls. This reactor is rated at 1029 kv-a, three phase, 60 cycles, 300 amperes and has 7.5 percent reactance on a 26 400 volt line.

In some applications of limited space requirements, the magnetic shield may be attached to the reactor, as in Fig. 8. In this case the magnetic shield is provided

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on two sides and on the top and bottom. This form of shielding has the advantage of reducing the eddy losses in the winding when strap conductors are used, because the presence of the magnetic shield over the top tends to direct the flux straight up through the coil. The side shielding alone is, however, somewhat simpler and easier to build.

In an ordinary air-core reactor, approximately 85 to 90 percent of the ampere-turns are used in sending flux through the air core in the center of the coil, and the remaining 10 to 15 percent ampere-turns are used in the return path in the region outside the coil. When the magnetic shield is used in the oil-immersed construction, the 10 to 15 percent of ampere-turns normally required in the outer region are reduced to a small value, on account of the lower reluctance of the shield. For this reason the reactance at normal current will be from 10 to 15 percent higher than without the iron. Under short-circuit conditions the magnetic return circuit becomes saturated and the reactor acts as if it were not enclosed with magnetic material. In actual operation this effect is of no consequence, the reactor rating simply being based on the short-circuit reactance. That is, a ten percent reactor will give ten percent reactance on short-circuit and about eleven percent reactance at normal circuit full load.

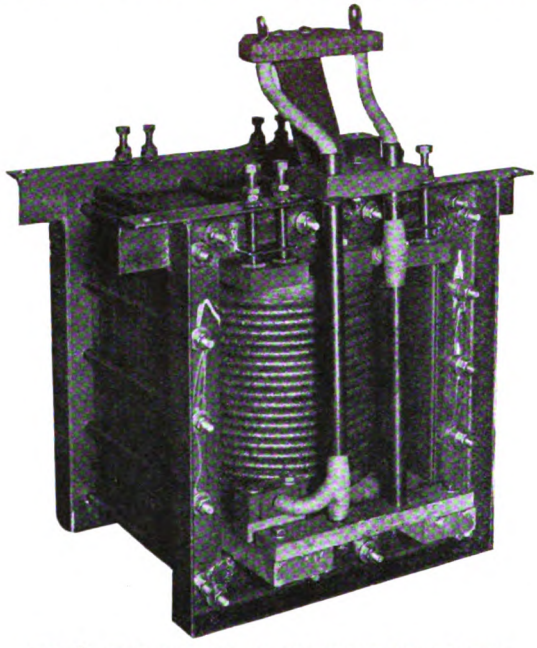

FIG. 8—THE COIL OF AN OIL-IMMERSED REACTOR
With the magnetic shields lining the tank well. The capacity is 101 kv-a on single phase, 60 cycles, 400 amperes. On a 12 000 volt line the reactance is 3.75 percent.

The coil for an oil-immersed reactor follows transformer practice in general, except that for the lower voltages and heavier currents the conductors may be in the form of stranded cables, in order to reduce the eddy current loss. In Fig. 9 are shown the coils of the three-phase reactor used in the case illustrated in Fig. 7. The winding is of the straight cylindrical type, with alternate layers wound from top to bottom and from bottom to top on solid micarta tubes. For the higher voltage applications strap-wound pancake coils may be used to advantage. The external appearance of the reactor, as shown in Fig. 10, is practically the same as a transformer.

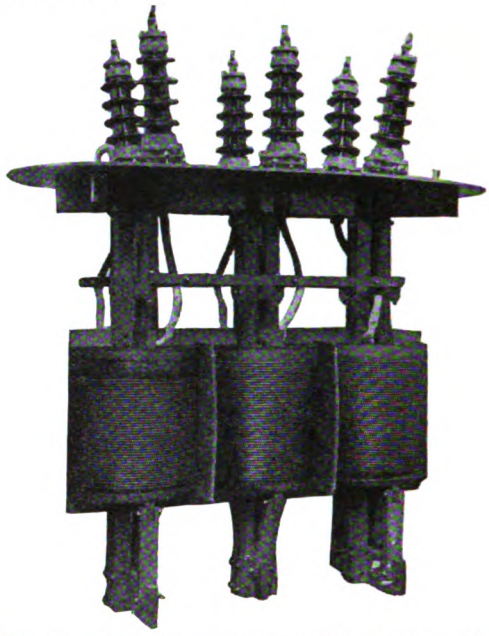

FIG. 9—THE COILS OF THE REACTOR WHOSE TANK IS SHOWN IN FIG. 7

The problem of reducing the effects of the stray magnetic field in a reactor may be approached from another angle. In the method already described the stray magnetic field is shunted from the tank wall by an enclosing magnetic circuit of low permeability. The other method is to generate by induction an opposing field in an effort to keep the flux from entering the tank walls. In this case short-circuited metallic rings

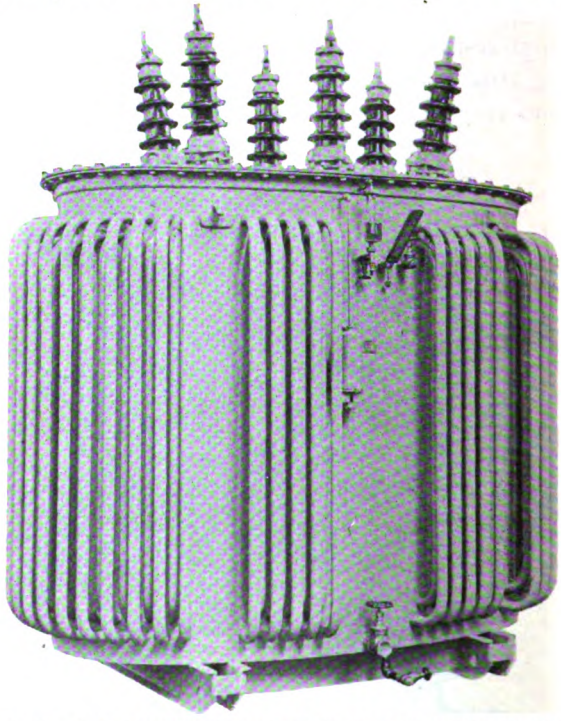

FIG. 10—A COMPLETELY ASSEMBLED OIL-IMMERSED REACTOR
The tank of this reactor is shown in Fig. 7.

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are placed around the reactor coil between the coil and the tank walls. Voltage is induced in these turns by transformer action from the reactor coil, and the resultant current sets up a magnetic field in opposition to the main field, tending to direct the return flux through the region between the coil and the short-circuited turns. This method gives conditions similar to a transformer with a short-circuited secondary, having losses in two windings instead of one, and having mechanical forces between the windings, which may be very great during periods of short-circuit on the system.

### ADVANTAGES OF THE OIL-IMMERSED REACTOR

The first big advantage of the oil-immersed construction is that reactors can be built with a high safety factor, for voltages on which the dry reactor is not considered safe from an electrical point of view.

The windings of the oil-immersed reactor are similar in both design and bracing to that of the transformer. Being immersed in oil, the windings have high dielectric strength and large thermal capacity. The oil-immersed reactor is, therefore, inherently suited for high-voltage and for outdoor applications where expensive compartments may be eliminated.

Since practically all the magnetic flux is confined within the tanks in oil-immersed reactors, there is no stray external field to cause heating and losses in adjacent steel structures, nor are there any appreciable magnetic forces between reactors. This avoids all use of external bracing and permits mounting oil-immersed reactors as near together as other conditions permit. Obviously the steel tank affords mechanical protection and prevents foreign materials from entering the windings.

With this development, satisfactory reactors may be furnished for limiting short-circuit currents in any circuit for which a transformer may be designed.

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# Characteristics of Direct-Current Motors and Generators for Diesel-Electric Ship Propulsion

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Westinghouse Electric & Mfg. Co.

THE use of Diesel-electric propulsion for vessels of all kinds has grown remarkably in the last few years. For this purpose the many desirable features of variable voltage control have caused the direct-current installations to outnumber considerably those making use of alternating current. The advantages of a direct-current propulsion system employing changes in the generator voltage to secure motor speed control are familiar to those engaged in marine work but the following are important enough to deserve further mention:—

1—Ease and simplicity of operation and a large number of economical running speeds, combined with a positiveness of adjustment which eliminates much unnecessary maneuvering and minimizes the danger of accidents.

2—The possibility of dividing the load among a number of engines and generators, thereby providing greater reliability and the possibility of maintaining operation under reduced power, upon the failure of one engine or the withdrawal of one generating set for auxiliary power purposes. Under this condition, full power may be utilized from the remaining units in operation.

3—The use of the most economical engine speed and the most economical propeller speed, with the numerous advantages of electrical gearing between these two elements and the resultant saving in weight and space.

4—The possibility of obtaining higher speed at full horsepower on certain boats under unloaded conditions or conversely the utilization of full generated horse-power at reduced speeds under loaded conditions. This is of especial advantage in towboats.

5—Good weight distribution throughout the entire boat.

6—Flexibility of connections, permitting the use of the main generating equipment for auxiliary power when in port, thereby eliminating on some types of boats, considerable auxiliary generating equipment.

When the first direct-current systems were installed an effort was made to use the type or equipment already developed. It is inevitable, however, that machinery for any class of service will, in the course of time, acquire certain design features peculiar to itself, and marine equipment is no exception.

Continuity and reliability of service are, of course, of paramount importance in any class of work, but especially is this true in marine work. This needs no explanation when one considers the difficulty of making extensive repairs without returning to shore and putting the entire ship out of commission for a number of days. At the same time, the equipment must be made as small as possible to reduce the weight and space occupied by machinery, leaving as much available cargo space as possible.

At first, the above two requirements appear to work against each other. The only solution lies in the use of good material in every machine and a well-proportioned design, utilizing all of this material to the best advantage. Every part of the machine must be worked up to but not beyond its capacity and all excess material must be eliminated.

The majority of direct-current installations on shipboard have used the Diesel engine as a prime mover. The characteristics of this engine, chief among which is its fuel economy, are such as to make it peculiarly applicable to this class of service. In fact the Diesel engine deserves a good share of the credit for the success and popularity of direct-current propulsion. Likewise the Diesel engine is the cause of a great number of the spe-

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cial features embodied in the design of direct-current propulsion generators. Consequently, the discussion on propulsion generators in this article will be limited to generators employing Diesel engines as prime movers.

The normal full-load speed of a Diesel engine is usually higher than the speed of a reciprocating steam engine of the same rating and yet is much below the speed of a corresponding motor-generator set or steam turbine. Consequently, the use of the Diesel engine has, caused the development of a new speed class of generators.

Another characteristic of the Diesel engine is its adaptability to a continuous rating rather than a nominal rating with short-time overloads. For this reason, Diesel engine-driven generators are practically always given a continuous rating, usually either 40 degrees or 50 degrees depending upon the operating ambient temperature. This results in the propulsion motor being given a continuous rating as well, since its sole source of power is the Diesel-driven generator. Thus the rating of the entire propulsion system is governed by the characteristics of the engine.

Diesel-engine service presents a much more rigorous mechanical application than a steam engine, on account of the high rate of acceleration at starting, and the greater vibration. An analysis of these requirements and of their effect on the generator has resulted in certain additional features being embodied in the construction of generators for Diesel-engine drive. Additional strengthening is applied to the rotor at several points which are considered most liable to suffer from the effects of this type of drive.

Due to the uneven torque, the mechanical requirements of the propulsion motor are more severe than those encountered in the ordinary industrial application.

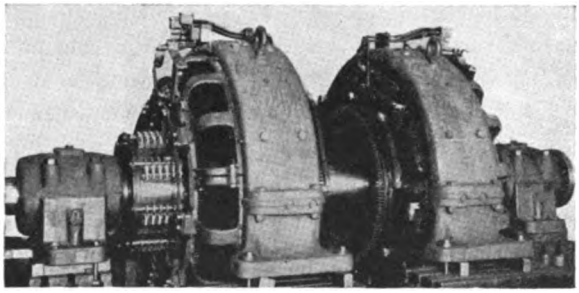

FIG. 1—A SHOP VIEW OF A TYPICAL OPEN TYPE, DOUBLE-ARMATURE, PROPULSION MOTOR

As a consequence, it is good practice to use practically the same mechanical refinements in the motor as in the generator.

Diesel-driven generators possess one design characteristic in common with generators for steam-engine service, namely, integral construction of armature and commutator spiders. This enables the generator manufacturer practically to complete the assembly of the machine without the shaft, which is quite often furnished by the engine builder. In the case of the propulsion motor, it is not necessary that the armature and commutator spider be of integral construction, since the motor manufacturer usually supplies the motor shaft.

Moisture-laden air exerts a deleterious effect on ordinary insulation, especially in salt water service. Consequently special insulation is used and additional treatments are given, both before and after assembly, on all insulated parts of generators and motors for propulsion service. Insulating materials and treatments are selected with a view to obtaining great dielectric strength and high moisture and heat resisting qualities.

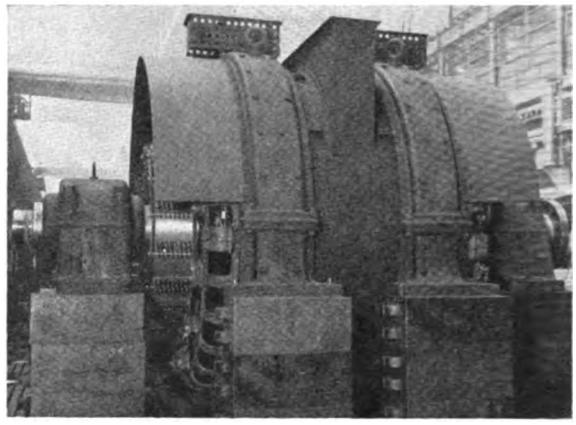

FIG. 2—A SHOP VIEW OF A LARGE, DOUBLE ARMATURE, FORCED VENTILATED PROPULSION MOTOR

With drip covers over the commutator. The air enters between the two armatures and is discharged over the commutators. This motor supplies 3200 hp to the propellor of an old tanker in conjunction with four 700 kw. marine generators. This forms one of the largest direct-current electrical plants installed on shipboard to date.

Much difficulty has been found in marine service in maintaining perfect sliding surfaces between the brush and the brushholder box when this box is made of iron or steel, no matter what non-corrosive treatments are given it. It is absolutely essential to the good operation of the machine that the brush be free to move in the brushholder box. This trouble is eliminated by the use of brass brushholders.

For Diesel-electric propulsion double-armature motors are used in the majority of cases, on account of the limited distance between the bottom of the boat and the propulsion shaft or center line of the motor armature. Of course, the reduced height and width of motor space is obtained at the expense of practically doubling its length (along the length of the ship) but this usually is not objectionable. Incidentally this arrangement makes for added reliability, since the two armatures are always connected in series, and headway at reduced speed is possible with one armature disabled. Figs. 1 and 2 illustrate typical double-armature motors.

Forced ventilation is quite common in connection with propulsion machinery. This is usually done to meet space and weight requirements, since it permits a smaller machine for a given rating than is possible with an open, self-ventilated design. In some cases,

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however, the surrounding air is too hot or impure for cooling purposes, and forced ventilation is used for the purpose of bringing suitable ventilating air from a source outside the engine room.

The sheet-steel cover over the upper half of the commutator in Fig. 2, is known as a drip cover, to protect the machine from the condensate which forms on

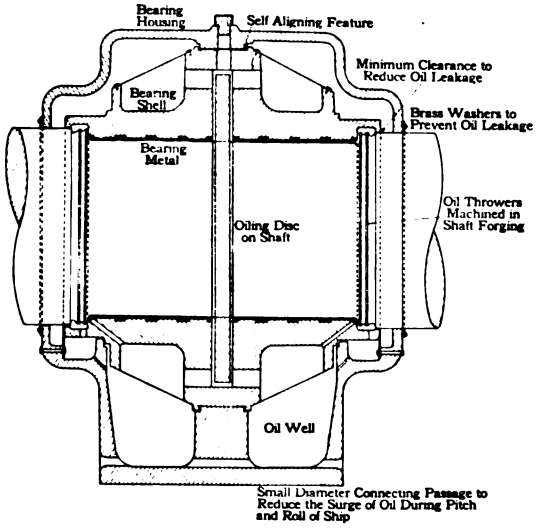
Bearing Housing
Self Aligning Feature
Minimum Clearance to Reduce Oil Leakage
Bearing Shell
Brass Washers to Prevent Oil Leakage
Bearing Metal
Oil Throwers Machined in Shaft Forging
Oiling Disc on Shaft
Oil Well
Small Diameter Connecting Passage to Reduce the Surge of Oil During Pitch and Roll of Ship

FIG. 3—A CROSS-SECTIONAL VIEW OF A MARINE BEARING

the underside of the deck above. A drip-proof machine is obtained by the use of these covers on both the front and rear of the machine. A forced-ventilated machine, as in Fig. 2, is made drip-proof by the addition of a cover on the commutator end only.

In connection with space requirements, it should be mentioned that the larger propulsion motors and generators manufactured by the Westinghouse Company always have the frame and the brush rigging split at the horizontal centerline to facilitate removal for inspection and repairs. Occasionally it becomes necessary to equip a propulsion motor or generator with compensating windings. These windings are in the pole faces and are of heavy copper strap of sufficient capacity to carry full-load current. Consequently, provision is always made for the ready splitting of the compensating winding connections at the horizontal centerline.

Most of the design characteristics discussed heretofore have not been such as would always enable one positively to indentify an uninstalled propulsion motor or generator by a cursory inspection. There are some very apparent features of marine design, however, which enable one to recognize a propulsion motor or generator, in any surroundings, at a glance.

One of these is a reduced dimension between the center line of the frame and the bottom of the foot. This dimension is commonly known as foot-height and propulsion motors and generators practically always employ a short foot-height. In the case of the generator, this is due to making the generator foot-height correspond to that of the engine which drives it. The Diesel engine usually employs a foot-height which is shorter than the standard foot-height of a direct-current generator of the same rating. It is very advantageous, if not essential, from the standpoint of ship construction, to have this dimension the same on the engine and generator. When the generator is equipped with an overhung exciter (as is usually the case) the exciter foot-height is made the same as that of the main generator.

The propulsion motor also usually has a shorter foot-height than a motor of corresponding rating for other classes of service. The reason is entirely different in this case, however. When the boat operates under momentary inclinations, the pedestal is subjected to strains directly proportional to its height. Also any vibrations present on the ship will be transmitted to the motor more readily, the greater the pedestal height. Consequently the pedestal is made as short as possible and the pedestal base is made unusually broad and sturdy. The frame foot-height is made short to correspond to the pedestal height and facilitate mounting on the ship's structure. To lessen vibration and distribute the stress in foundation members, each foot is drilled to accommodate four relatively small holding down bolts instead of two large ones as in other classes of service.

The electrical manufacturer always furnishes the bearings and shaft of the propulsion motor. For reasons already given, these bearings are usually equipped with much shorter pedestals than corresponding ones for industrial service. To meet the difficult requirements of marine service, the Westinghouse Company has developed an entirely new and distinct line of marine bearings to cover a large range of ratings. A sketch of one of these bearings is shown in Fig. 3.

The bearings of marine motors have a number of distinctly marine features. They are extremely rugged, being stronger in every detail than an industrial bear-

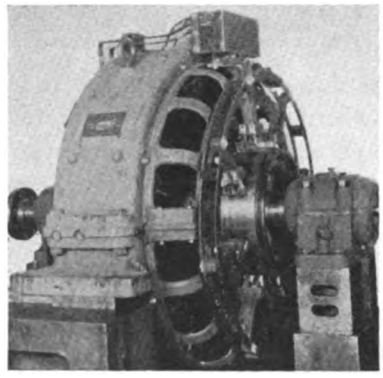

FIG. 4—A TYPICAL SINGLE-ARMATURE, OPEN TYPE, PROPULSION MOTOR

ing of the same rating. Positive lubrication is assured regardless of speed or direction of rotation of the shaft, or inclination of the boat. A central disc secured to the shaft dips into the oil reservoir at the base of the pedestal, carrying the oil to the top, where it is deflected to both sides of the bearing, giving an ample supply of oil to the shaft at all times.

This bearing is split horizontally and babbitted over the top half as well as the lower. It is self-aligning

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and special precautions are taken to prevent oil leakage by reason of the conditions under which a boat must necessarily operate. Another feature is a double oil well with restricted connecting passage to prevent the surge of the oil under momentary inclinations. Because of these special features the bearings operate satisfactorily during momentary pitches of 15 degrees and momentary rolls of 30 degrees.

In the case of double-armature motors, only two bearings are furnished. This arrangement is satisfactory at speeds such as are encountered in this class of service, and is more economical than a three-bearing arrangement as regards space, weight and cost; also the two-bearing arrangement permits easier maintainment of alignment. The double-armature propulsion motor in Fig. 2 is equipped with two marine-type pedestal bearings.

Occasionally the electrical manufacturer furnishes the shaft and one or two pedestal bearings for the propulsion generator. In this case it is desirable to make the frame foot-heights of the generator and exciter the same as that of the pedestal, but if necessary they can be made to correspond to the foot-height of the

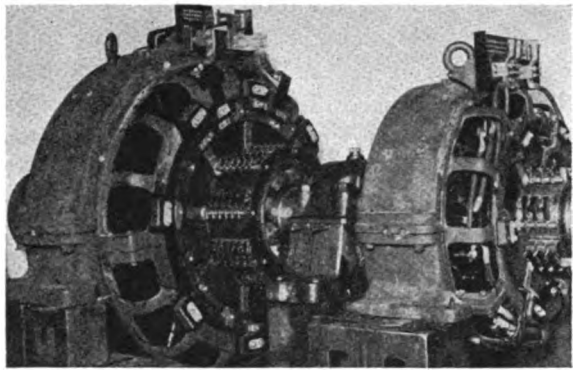

FIG. 5—A PROPULSION GENERATOR WITH SHAFT, OVERHUNG EXCITER, AND ONE PEDESTAL BEARING

Diesel engine and the short marine pedestal can be mounted on a structure of slightly different height. A propulsion generator with shaft, overhung exciter, and one marine type pedestal bearing is shown in Fig. 5, employing equivalent foot-heights on generator, exciter and bearing.

It is almost universal practice to utilize speed magnetos on the propulsion motor shaft to indicate the propeller speeds. The magneto is usually mounted during the installation of the motor.

The arrangement of the terminals on propulsion machinery is a distinctive feature peculiar to this class of service. In most industrial applications the leads to the machine are brought up through the foundation to the terminals which are on the side or bottom of the machine. In the case of marine equipment, the propulsion machinery is located in the extreme lower part of the ship, and the leads are usually carried overhead and brought down to terminals located on the top of the machine, Fig. 6. It is customary to supply removable sheet metal guards around the terminals to minimize the danger of accidental short-circuit or contact with live parts. These terminal guards are shown in Figs. 2, 4, 5 and 6.

The variable-voltage control scheme used on propulsion systems makes use of pure shunt-wound, sepa-

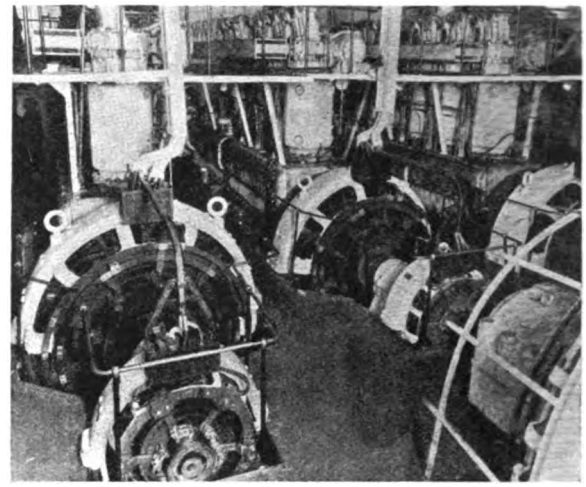

FIG. 6—VIEW OF ENGINE ROOM ABOARD AN OIL TANKER

rately-excited motors and generators. The motor field is excited at constant value in one direction, while the generator excitation is varied from zero to maximum in either direction, thus varying the generator terminal voltage and hence the voltage impressed on the motor armature. The engines run at constant speed, and the motor speed varies with the generator voltage. Thus another distinguishing characteristic of propulsion motors and generators is a pure shunt-field winding, designed for a separate excitation voltage which is not necessarily the same as the armature voltage.

The excitation power mentioned above is secured from a small compound-wound auxiliary generator,

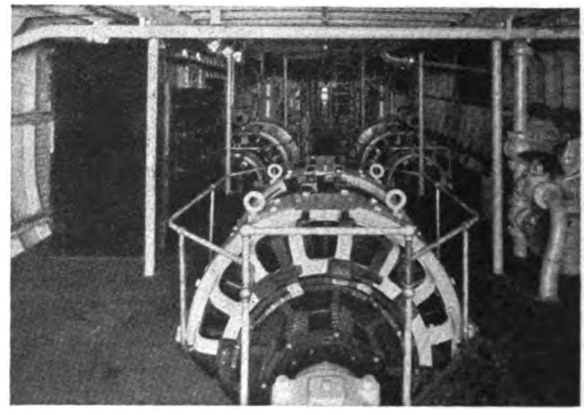

FIG. 7—A DIESEL-ELECTRIC POWERED TUGBOAT
Showing the arrangement of the motors with respect to the diesel engines and the generators.

almost invariably overhung on an extension of the generator shaft. The exciter is similar in design and appearance to the propulsion generators except that it is compound wound, self-excited and smaller in size.

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# An Extension of the High-Power Testing Laboratory

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THE general design of control and switching apparatus has been steadily improved until it is now almost a fine art. It is not particularly difficult to make devices that will do the work required satisfactorily, but to make them in the best way requires painstaking investigation, voluminous tests, and careful analysis of results. By the best way, is meant at a minimum of cost and space to give adequate and reliable performance in service. An engineer charged with the responsibility of producing equipment that will meet these specifications must have tools or equipment for carrying out the necessary investigation of the effects of the various variables, and to obtain the fundamental data necessary to a consistent and adequate design.

As a typical illustration of the type of investigation which is necessary in work of this nature, consider the problems in the design of alternating-current contactors commonly applied to control motors in industrial service, and to some extent in the control of power house auxiliaries. Such a contactor must meet the following specification:—

1—It must operate a large number of times in starting the motor or adjusting the speed of the motor without:
*a*—Undue wear which would affect its serviceability or require too frequent replacement.
*b*—Erosion of contacts sufficient to cause overheating due to poor contact.
*c*—Burning or melting of contacts sufficient to cause them to weld.
*d*—Failure of insulation to frame or between phases.
2—In some applications the contactor must not be damaged mechanically or electrically by the maximum possible short-circuit current which can flow in the circuit for a sufficient length of time for the circuit-breaker protecting the feeder to open the short-circuit and clear the fault.

To demonstrate the adequacy of any design to meet these requirements requires a test under the operating conditions or the equivalent, so far as current and voltage are concerned. This requires current and voltage simultaneously, which means kv-a, and consequently requires a high kv-a capacity testing plant.

The high-power alternating-current testing laboratory* was designed primarily for the testing of oil circuit breakers and was placed in operation in November, 1925. This provided facilities for testing at high values of current from 3800 volts up to 13 200 volts, three-phase. The field of investigation at high currents below 3800 volts was not covered. However, recent additions to this laboratory have extended the range to lower voltages, and now it provides for the field of low-voltage, high-current investigations.

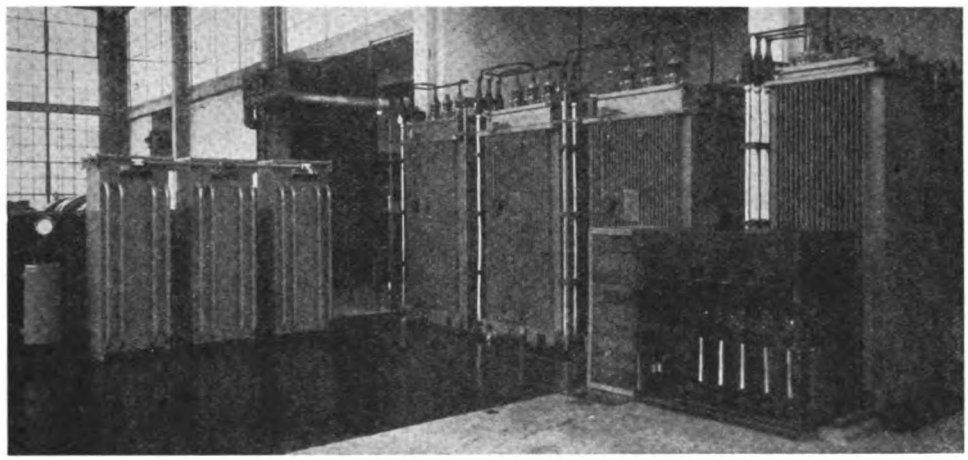

FIG. 1—REAR VIEW OF TRANSFORMER BANK
Showing three single-phase balance coils in the rear and terminal cabinet and area for testing rectifiers in the foreground.

This extension of the high-power laboratory has been designed primarily for the testing of alternating-current contactors. It is also well adapted to producing high momentary current, which will be of great use in experimental study of the mechanical stresses in circuit breakers and switching structures. It is particularly well suited for the study of the effect of high current stresses on circuit-breaker closing mechanisms. The facilities are such that single-phase currents as high as 120 000 amperes r.m.s. can be passed through the leads and contacts of an oil circuit breaker. Approximately 60 000 amperes r.m.s., three-phase can be passed through the poles of a three-phase circuit breaker.

The power for these tests is supplied from a bank of three 1000 kv-a transformers of low inherent reactance, having eight secondary windings, each of which has a normal voltage of 287.5 volts. These eight wind-

*Described in the JOURNAL for March 1926.

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ings may be connected in all series and parallel combinations, and also in delta or star, three-phase, or in series or parallel, single-phase, giving voltages from 287.5 to 4000 volts, three-phase and from 287.5 to 6900 volts, single-phase. To give further flexibility, a three-phase autotransformer is provided for the primary supply circuit, and arranged to buck or boost the supply voltage approximately 25 percent.

It is obviously impossible in such a laboratory to provide actual motors as a load for adjusting the current value desired for a given test. It was, therefore, necessary to provide adjustable impedances having characteristics equivalent to those of a motor. The starting currents of a motor are of relatively low power-factor, and it is well known that it is more difficult to interrupt currents of low power-factor than currents approaching unity power-factor. It was, therefore, considered desirable to provide reactors for controlling the load current, as they would represent the most severe condition which could possibly be obtained in service, and would give some margin of safety over actual operating conditions.

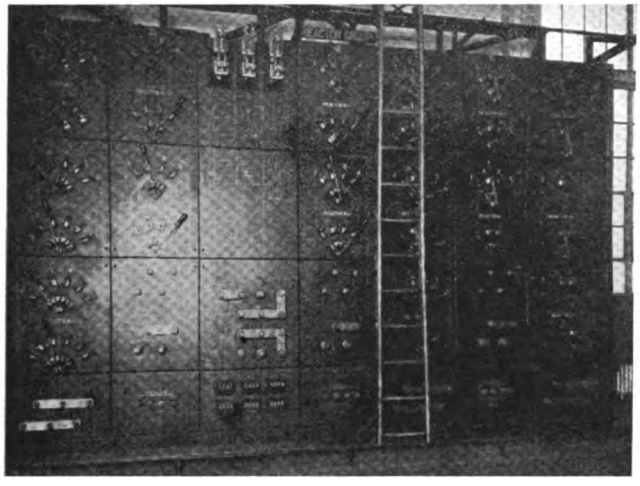

FIG. 2—FRONT VIEW OF REACTOR CONTROL BOARD
Showing swivel switches for selecting taps, terminal boards for series or parallel and star or delta connections and truck ladder for reaching upper switches.

Due to the wide range of currents and voltages that were involved it was not easy to devise a set of reactors which would be reasonable in size and of sufficient flexibility to meet all of the conditions. After considerable study a reactor group was designed consisting of 15 units, each unit being provided with a number of taps which were connected to swivel switches, as shown in Fig. 2, so arranged that all possible combinations of taps could be utilized. Impedance values from a few percent up to the maximum value of each reactor are thereby available in practically even increments. The reactors may also be connected in series or in parallel in each phase, and the phases may be connected in star or delta combination for three-phase testing, and also in series or in parallel for single-phase testing. By this means currents from a few amperes at 2400 volts up to currents of 30 000 amperes at 287 volts can be obtained.

The complete reactor group is so arranged that the device being tested can be placed between the source of power and the reactor, so that the voltage between phases will be substantially maintained while the current is flowing. The transformers supplying power have purposely been made with low reactance, so as to maintain this voltage at a high value. The reactors can also be placed between the source of power and the device being tested, where such a condition is desirable. This would apply particularly to the use of alternating-current contactors for the control of power house auxiliaries, where the contactors are not normally expected to interrupt the short-circuit current which might flow in case of failure of the motor, but which will probably drop out due to the drop in voltage resulting from such a short-circuit, and thereby at least attempt to open the circuit at greatly reduced voltage between phases. The ability of contactors to open a given current under such a condition is doubtless much greater than when the voltage between phases is maintained at nearly normal value. Portable resistance racks are provided for introducing resistance into the test circuit for the smaller current values.

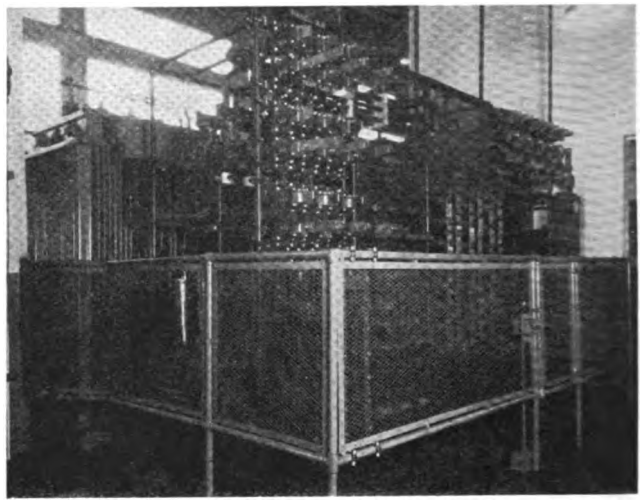

FIG. 3—FRONT VIEW OF TRANSFORMER BANK AND CONTROL BOARD

A small steel cabinet for mounting outside of the laboratory is provided for testing oil-immersed devices in which there is a certain hazard of oil explosion, making tests within the building undesirable.

Complete permanent equipment provided for making electrical measurement includes current and potential transformers and a nine-element oscillograph. A cycle drum is provided for automatically controlling a repeating cycle of operation.

The same general control scheme used in other parts of the high-power laboratory previously described is provided in this new addition. Automatic relay equipment is set in motion when the operator closes the test switch by means of an insulating hook stick. This operation causes the oscillograph and other relays to act

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in proper sequence to obtain the desired test and record. By using an insulated hook stick the operator can stand entirely clear from all electrical connections, so that if something should go wrong and high voltage gets into the oscillograph or control circuit the operator is not endangered. These safety precautions have proved their value, as no matter what precautions are taken, something goes wrong sooner or later, and without this safety feature the life of the operator might be endangered.

This transformer bank has also been made adaptable for supplying the alternating-current power to a six-phase rectifier operating at either 600 volts, 750 volts or 1500 volts direct-current up to 3000 amperes at the lower voltages and 1500 amperes at 1500 volts. The direct-current end of the rectifier will be loaded back on the generators forming the power equipment in the direct-current high-power testing laboratory.** This will permit protracted runs on rectifiers under full load and full voltage. This rectifier equipment is also arranged so that it may be connected in series with the direct-current generators for short-circuit testing on 3000 volts direct-current, thereby doubling the capacity available for such testing.

In addition to the specific testing which has already been mentioned, this equipment will be used for a great deal of miscellaneous experimental work of a development nature requiring voltages and currents within the range covered. Among these items may be mentioned:—

*a*—Current carrying capacity of multiple bus-bars.

*b*—Current interrupting ability of fuses.

*c*—Probability of faults in cables on low-voltage network burning free.

This addition to these laboratories greatly increases the range of tests and investigations that can be handled efficiently and quickly, and will result in a material improvement in design details and more definite knowledge of the proper limits of application of the various electrical devices that can be readily tested.

**Described in the JOURNAL for October 1927.

# Selecting the Most Desirable Type of Direct-Current Generator

SCOTT HANCOCK
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Westinghouse Electric & Mfg. Co.

THE electrical characteristics of direct-current generators vary widely. On this account the generator which may be suitable for one application may be totally unsuited to another; and conversely the characteristics desired from a generator for different applications may differ widely. The selection of the proper type of generator for a particular application will greatly increase the satisfaction obtained by the user from the machine.

The chief differences in electrical characteristics between different varieties of direct-current generators are found in their volt-ampere curves. These volt-ampere or regulation characteristics are determined chiefly by the field windings used, although they are also determined to a lesser degree by the design of other parts of the machine. Consequently, machines having the various types of characteristics are usually known by their field windings, as shunt, compound, differentially compound, separately excited, etc.

## SHUNT GENERATORS

A simple shunt generator is shown in Fig. 1. A schematic diagram showing the connection of such a generator is shown in Fig. 2. Typical volt-ampere curves of a 125 volt generator are also shown in Fig. 2. The different curves shown in this figure as *A*, *B*, and *C* are each taken with a different setting of the field rheostat. The parts of the curves that are ordinarily used in operating are those shown as solid lines. Ordinary shunt generators cannot be operated satisfactorily below about two-thirds of the rated voltage, as below this value the voltage tends to be unstable. When specially ordered, it is possible to build a shunt generator which will operate down to about one third normal voltage without encountering trouble with stability. Such a generator is a little larger and more costly than an ordinary generator of the same rating.

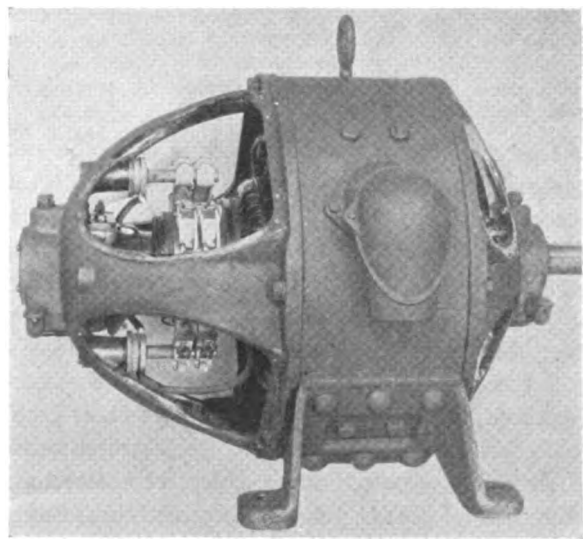

FIG. 1—A TYPICAL SHUNT WOUND DIRECT-CURRENT GENERATOR

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The construction and connections of the shunt generator are extremely simple. Hence, unless the characteristics produced by some other type are especially required, shunt generators are generally used. Shunt wound generators are used for a wide variety of applications, some of which are as follows:—

*Exciters For Use With Vibrating-Type Regulators*—Shunt machines are especially desirable for this type of application because all the main field windings are directly under the regulator control. If compound wound exciters are used, the regulator has control of only one part of the field, that is, it controls the shunt but not the series field. As a result, shunt machines are more responsive to regulator control and will react much more rapidly. In addition,

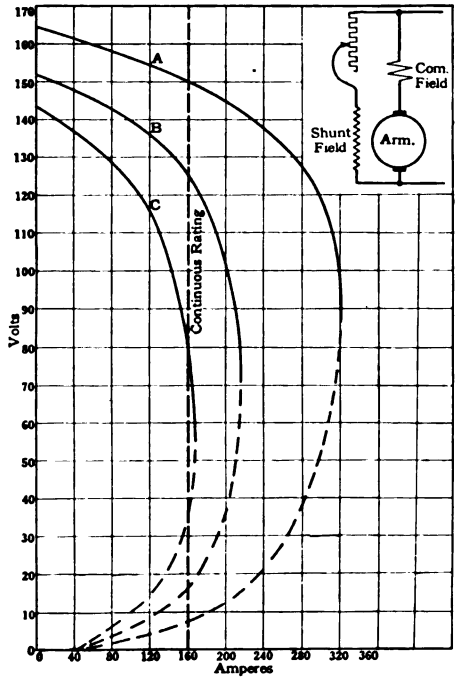


FIG. 2—CONNECTIONS AND REGULATION CURVES OF A SHUNT WOUND GENERATOR

Curves *A*, *B* and *C* were obtained by varying the field rheostat.

if a large amount of compounding is used the exciter may build up to an objectionably high voltage as a series machine, even when there is no current in the shunt field. When this happens, it is obviously impossible for a regulator to reduce the voltage.

*Charging of Single Lead Batteries*—The characteristic desired of generators for charging lead batteries without the use of any external resistance in the battery circuit is that the voltage shall drop off slightly with an increase of load. The ordinary shunt generator has approximately this characteristic and is often used for this purpose. When the battery is discharged the voltage is low and the battery can stand a heavy input in current without injury. As it becomes charged, its voltage increases and its current should decrease. The shunt generator automatically gives such characteristics. The rate of decrease of current is seldom or never ideal, but due to its simplicity and lack of possibilities of trouble, such as would be encountered if the current were reversed through a compound generator driving it as a motor, the shunt generator is the favorite for such an application.

*Generators for Trickle Charging Lead Batteries*—Sometimes a generator is connected to a battery and is continuously charging it at a very low rate. This is called trickle charging. The batteries used in central stations for operating the switches are usually charged in this way. There are two reasons why generators used for this work should be shunt wound. The first is that if the generator voltage for any reason should drop below the battery voltage and the battery feed current into the generator driving it as a motor, in a compound generator the series field would become differential. The machine would then run at a very high speed, possibly dangerously high, and would take a great deal of power from the battery. If the generator is shunt wound, it would tend to run merely at normal speed and would take but little power from the battery. The second reason is that, when the switches operate, they take a considerable load and cause the battery voltage to drop. If the generator is compound, it will try to supply power to keep the voltage from dropping and would have to be made large enough to carry the heavy load. Consequently, such a machine must be considerably larger than a shunt machine used for charging the batteries.

*Exciters to Operate Over a Wide Voltage Range When Under Manual Control*—Frequently it is desired to use exciters for synchronous machines without a rheostat in series with the field of the synchronous machine, and with the field current of the synchronous machine adjusted by manual control of the exciter field rheostat. Such exciters should be shunt wound. If they are made with any appreciable degree of compounding at the maximum voltage, they will be greatly over-compounded at the minimum voltage and it will be impossible to control them satisfactorily by means of the exciter field rheostat.

*Parallel Operation*—Shunt generators can be connected to operate in parallel. Doing so involves less wiring and fewer operating adjustments than with any other type of winding. Consequently, they should be used when machines are to be operated in parallel and when the characteristics of shunt generators are satisfactory. Compound machines can, of course, be operated satisfactorily in parallel, but the connections and adjustments are not quite as simple as for shunt machines.

### COMPOUND GENERATORS

The compound machine is one which has shunt coils such as are used on the shunt machines, and also series coils or field coils in which the armature current flows. A schematic diagram of such a

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machine is shown in Fig. 3. This series field may oppose or assist the shunt field. When it assists the shunt field the machine is known as additively compound, or more often the word additive is omitted and the machine is called simply a compound machine, while the generator in which the series opposes the shunt field is known as a differentially compound machine. The characteristics of a typical additively compound machine are shown in Fig. 3. This type of machine, should not be operated at a voltage much lower than rated. Its characteristics change with reduction of voltage much more than do those of the shunt machine, so it is more imperative that the compound generator be operated reasonably near the rated voltage than for the shunt generator. When the voltage is lowered, the effect of the compounding is much more prominent, a machine which is flat compounded at rated voltage becoming much over-compounded at a lower voltage. Also the hump, or deviation of the volt-ampere curve from a straight line, becomes much worse at voltages below rated.

*Power and Lighting Service*—Since by the use of the series winding a generator can be made to have approximately the same voltage regardless of load, and since it is desired to keep a constant voltage on lights or motors, the compound machine is most often used for applications where there is a lighting or general power load. This is one of the most usual applications for direct-current generators. For this application generators are sometimes made so that the voltage rises slightly as load is applied. This is done for two reasons, first, it tends to compensate for the *IR* drop of the line, and second, as the load usually is between a quarter load and full load, the voltage between these two loads remains more nearly constant if the no-load voltage is permitted to be below that at full load. A shunt machine is not very desirable for this application because if the voltage varies even slightly, the light from the lamps varies greatly. To maintain the voltage of a shunt generator constant requires either a regulator or very close attention from an attendant.

*Constant-Potential Motion-Picture Generators*—Two projectors are normally used in a motion picture theater. While one film is being shown from one machine, the motion picture operator is removing a preceding reel from the other machine and placing the subsequent reel in it. During this time the arc in the second machine is not going. When the end of the reel in the first machine is approached, the operator strikes the arc in the second machine and allows it to warm up. Then the instant the reel on the first machine ends the operator starts the second machine and then later breaks the arc on the first machine. Consequently, during most of the time a motion-picture generator is carrying the load of one projection machine, but there are intervals at the beginning and end of each reel when it must carry the load of two machines. If at this time the voltage of the generator materially decreases, it will result in a decreased light from the lamps and a dimming of the picture on the screen. To avoid this, motion picture generators must be made so that their voltage at normal load and at double load are approximately the same. Also, to be able to strike the arc readily the no-load voltage should not be much below the full-load voltage. To obtain such a curve the machine must be compound wound.

*Multiple-Operator Arc-Welding Generators*—Several welders may derive their power for arc welding from a common generator. Such a generator is ordinarily called a multiple-operator arc-welding generator. For this service the chief essential is

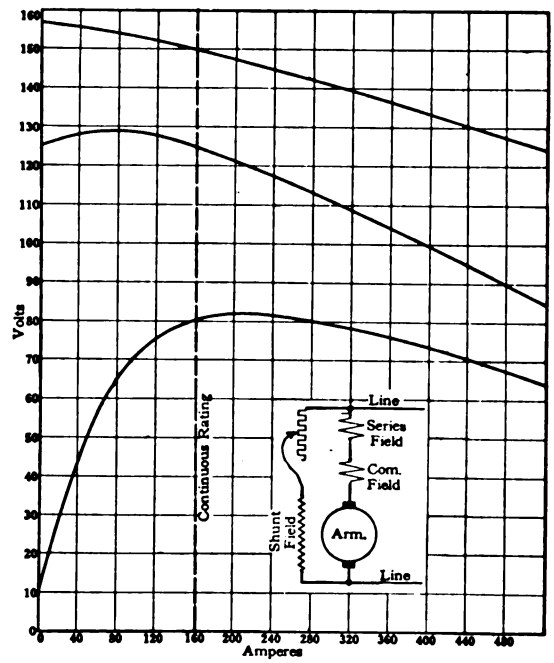


FIG. 3—CONNECTIONS AND REGULATION CURVES OF A COMPOUND WOUND GENERATOR

The regulation curves were taken with the series field aiding the shunt field.

that the voltage shall stay approximately constant regardless of the load. If the generator does not maintain such a voltage, and one operator is welding when a second starts, the increased load will cause a change of the generator voltage, resulting in a change of the current in the arc maintained by the first operator, so affecting his work. As with the motion-picture sets mentioned above, a multiple-operator arc-welding generator should be flat compound over the operating range. However, in this case the range is only up to rated load instead of double rated load.

*Exciters to be Used with Rheostatic Regulators*—When an exciter is used with a rheostatic regulator, the rheostat in the field of the synchronous machine and not the field on the exciter is under the control of the regulator. The regulator uses the exciter voltage on certain of its coils. If the exciter

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voltage varies excessively as the regulator changes the load on the exciter by changing the resistance in series with the field of the synchronous machine, then the regulator coils energized by the exciter voltage may at times be over-worked and be in danger of burning out. To avoid this, it is desirable that the voltage change due to change of load be not very great. For simplicity it is desired to use a shunt machine if possible. If two such exciters are to be operated in parallel, it is desired to have the voltage droop as load is applied, as such a droop eliminates the need of an overseer when paralleling. Consequently, it usually is desired to have a generator whose voltage decreases as load is applied, but which does not decrease excessively as load is applied. Sometimes the desired characteristics can be obtained from shunt generators, but usually their droop is too great, so under-compound generators are used.

*Exciters Used Without Regulators and Where a Rheostat is Used in the Main Field*—If the exciter is not to be used with a vibrating-type regulator, and if all the control of the synchronous machine's field current is obtained by an adjustment of the rheostat in the synchronous machine's field, then a compound exciter presents a slight advantage over a shunt exciter because a rheostat of lower resistance can be used in the synchronous machine's field. As the rheostat is cut in the voltage of a shunt exciter rises, so more resistance is necessary to reduce the field current to the proper amount, while with a compound exciter of flatter voltage characteristics the voltage does not tend to rise.

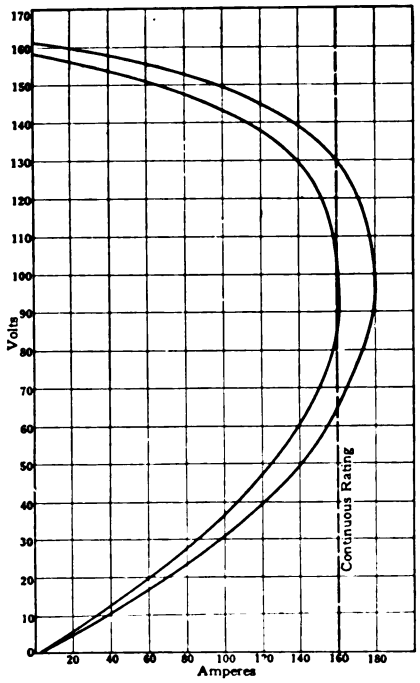


FIG. 4—REGULATION CURVES OF A DIFFERENTIAL COMPOUND GENERATOR

*Multiple Charging of Lead Batteries*—In most battery charging stations there is one generator which is used for charging a number of batteries. These batteries are in different conditions of discharge and are connected to the generator at various times. The charging voltage applied to the battery, when discharged should be less than when fully charged. Since various batteries all to be charged at once may have different conditions of charge, apparently the only way to get the right voltage on each battery and still use only one generator is to set the generator voltage higher than the voltage desired across the batteries and to use a resistance in series with each individual battery. The generator voltage and the resistance used are made such that if the generator voltage remains constant, the desired voltage will be across the battery at all times from the fully-discharged to the fully-charged condition. The generator must be made as flat compound as possible. If it is not flat compound, then when additional batteries are placed on charge, thus adding load on the generator, the generator voltage will change, thus changing the voltage at the terminals of all batteries and the current going through them. Since the battery is quite sensitive to small changes of voltage, it it essential that the generators be specifically designed for battery charging service, for even the normal flat-compound wound generator may have a hump in the volt-ampere curve large enough to cause trouble. By taking special precautions in the design of generators for this service, this hump can be greatly reduced.

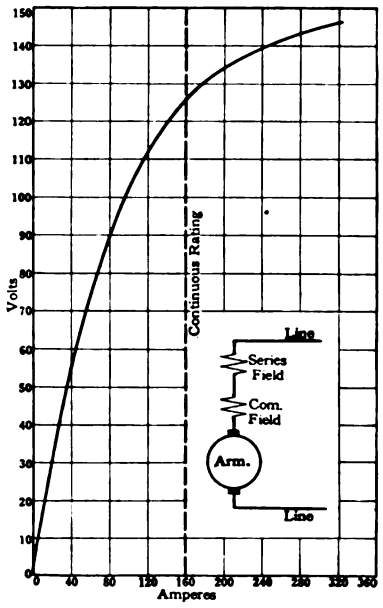


FIG. 5—CONNECTIONS AND REGULATION CURVE OF A SERIES WOUND GENERATOR

### DIFFERENTIALLY-COMPOUND GENERATORS

A differentially-compound generator is the same as an additively-compound one except that the series field strength opposes that of the shunt field instead of assisting it. Its diagram of connections is the same as shown in Fig. 3. Typical volt-ampere curves of such a generator are shown in Fig. 4. The

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two most usual applications for such a generator are given below:—

*Charging of Single Edison Batteries*—In contrast to lead cells, for which a tapering current is desired, in charging Edison batteries it is desirable to have approximately a constant current from the beginning to the end of the charge. As with the lead cells, the voltage across the battery increases as the charge progresses. It may be seen by referring to the curves of Fig. 4 that for a comparatively wide range in voltage the current is practically constant. By making the volt-ampere characteristics of a differentially-compound generator to suit the battery, this type of generator can be made to be almost ideal for charging Edison batteries. Thus, it ordinarily is used for this purpose.

It can be seen from Fig. 2 that similar characteristics can be obtained from a shunt generator. Actually, however, in practice it is found that to get equally good characteristics from a shunt generator a larger and consequently a more costly machine is needed. Therefore, differentially-compound generators are preferred.

*Series-Arc Motion-Picture Sets*—As explained previously, in motion-picture theatres sometimes two arcs are being operated at once and at other times only one. Sometimes instead of using two arcs in parallel, as mentioned previously, they are placed in series and the generator characteristics are made inherently drooping. By using this scheme there are no resistors in series with the arc and so the resistor loss is eliminated. A generator supplying power for motion-picture arcs so connected is called a series-arc generator. The two arcs in series are connected directly across the generator. When one only is operating the other is short-circuited. When the second one is to be struck its carbons are touched together, the short-circuiting switch is opened, and the carbons are drawn apart, thus establishing the arc. Then when the first arc is to be discontinued, it is merely short-circuited by a switch.

Most arcs inherently operate at a given voltage, usually around 65 volts. If the current desired in the arc was 100 amperes, then the volt-ampere curve should be such as to give 100 amperes at 65 volts when only one arc was operating and about 100 amperes at 130 volts when both arcs are operating. Differentially-compound generators can be made to have such characteristics, and so are regularly used.

### SERIES GENERATORS

In the series generator no shunt coils are used. The connections and a typical curve are shown in Fig. 5. There is only one application of a series generator that is at all usual.

*Booster Generator*—Frequently, it is desired to compensate for the resistance drop of a line carrying direct current, and it is desired to have this compensation take place at a considerable distance from the generator. In some way the voltage at some point on the line must be increased an amount equivalent to the voltage drop from the generator to that point. Since this drop is practically proportional to the load current, the voltage added should be directly proportional to the load current. The series generator, unless overloaded, gives such a characteristic as is shown by the curve of Fig. 5. No other type of winding will give a similar characteristic, consequently, the series generator is used here.

### SEPARATELY EXCITED

Direct-current generators are sometimes excited from some source of power other than their own armature. Such generators are said to be separately excited. In addition to the separately-excited windings, they may have a variety of other types of windings, as, for example, they may have shunt coils and series coils excited in the usual manner. Separately-excited generators of any type are used only when

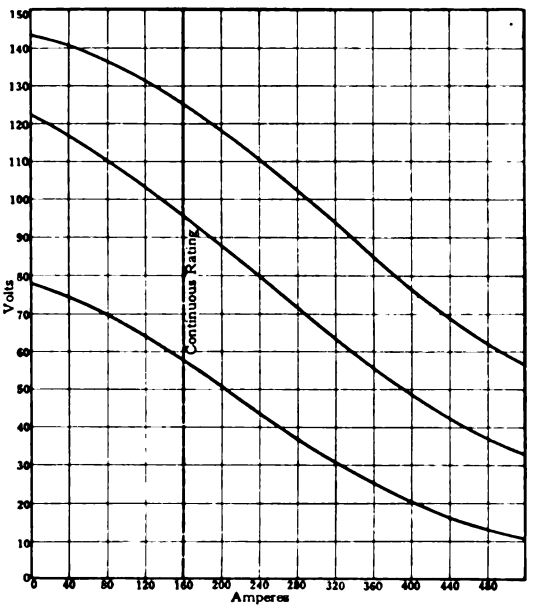


FIG. 6—REGULATION CURVES OF SEPARATELY EXCITED SHUNT GENERATOR

none of the generators previously mentioned would be suitable, for the separate excitation, requiring the use of an exciter, adds complication and cost. The most usual of the various combinations of windings that are used and the application for which it is used will be given.

*Separate Excitation—No Compounding*—Separately-excited generators without series fields or without self-excited shunt fields are used as the generators of variable-voltage sets for single-motor paper machines. The voltage, due to the *IR* drop in the generator and to the effect of armature reaction on the generator, decreases slightly as load is applied, but the decrease is not great enough to be objectionable. Curves of such a generator are as shown in Fig. 6.

Separately-excited windings are sometimes used when the voltage of the generator is not suitable for

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use for excitation. For example, radio generators have rated voltages of 1500 volts or more. It is not feasible to make shunt fields and rheostats for such voltages, particularly on small machines, so such generators are made separately excited.

*Separate Excitation—Differentially Compound*—In this case the shunt field is excited from a constant-voltage exciter, but a series field is energized by the armature current of the generator, being connected to oppose the separately-excited field. Such a machine has drooping curves such as are shown in Fig. 7. The most usual application for this type of generator is for single-operator arc-welding generators. The voltage is drooping as is desired to give a stable arc; the welding current can be adjusted over a wide

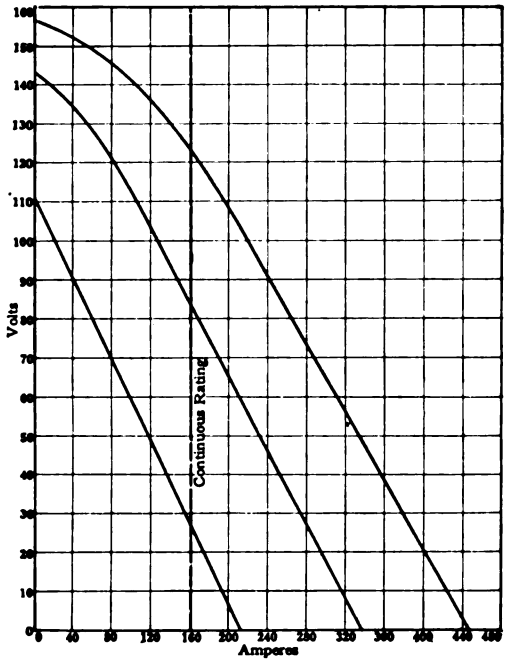


FIG. 7—REGULATION CURVES OF A SEPARATELY EXCITED SHUNT FIELD, DIFFERENTIAL SERIES FIELD GENERATOR

range by varying the shunt-field current; the generator is entirely stable at any setting; and the voltage will build up or down rapidly.

*Separate Excitation—Self Excited and Differentially Compound*—If, to the separately-excited compound generator just described, is added another shunt field excited by the armature voltage of the generator itself, we have a separately-excited, self-excited, differentially-compound machine. Typical curves of such a machine are shown in Fig. 8. Such machines have been used for single-operator arc-welding generators. The curves obtained are slightly more desirable than those obtained by a separately-excited, differentially-compound wound generator, but the responses of the voltage to changes of the arc length are more sluggish and so less desirable. This type of generator also is being used and is desirable for such applications as variable-voltage electric shovels. The drooping curve causes the motor to which the generator supplies power to stall if it encounters too heavy a load. The self-excited shunt field tends to give a more nearly constant current over a wide voltage range, so causing the motor's torque to be more nearly constant over a wide speed range. It also makes more sluggish the changes of voltage of the generators, tending to cut down sparking as the generator voltage is built up. The separately-excited field makes the generator stable under all conditions, helps to give the desired volt-ampere curves, and supplies the means of adjustment of the current and voltage.

## CONCLUSION

To obtain the most desirable results for various applications of direct-current generator, generators of the types as indicated below should be used.

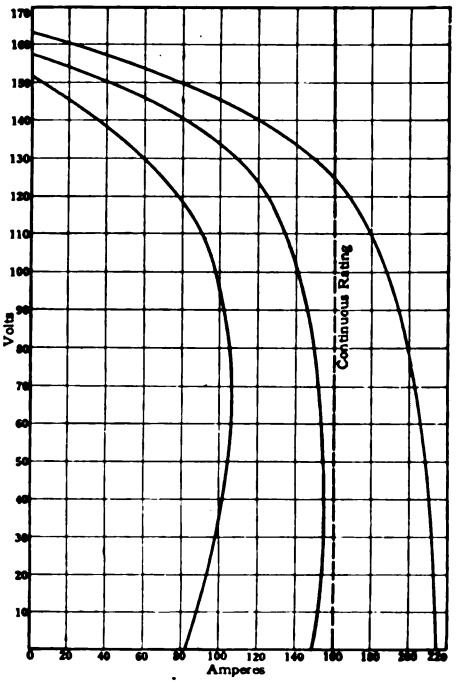


FIG. 8—REGULATION CURVES OF A DOUBLE SHUNT FIELD, DIFFERENTIAL SERIES FIELD GENERATOR

One shunt field is self excited, the other is separately excited.

| APPLICATION | TYPE |
|---|---|
| Arc welding, multiple operator | Compound |
| Arc welding, single operator | Separately excited, differentially compound |
| Battery charging for Edison batteries, single | Differentially compound |
| Battery charging of lead batteries, Multiple | Compound |
| Battery charging of lead batteries, Single | Shunt |
| Battery charging, trickle, of central station lead batteries | Shunt |
| Boosters | Series |
| Exciters, constant voltage under manual control | Compound |
| Exciters used with rheostatic regulators | Compound |
| Exciters used with vibrating type regulators | Shunt |
| Exciters, wide voltage range, manual control | Shunt |
| Extremely high or low voltage | Separately excited |
| Motion picture, constant potential | Compound |
| Motion picture, series arc | Differentially compound |
| Power and lighting | Compound |
| Variable voltage | Separately excited |
| Variable voltage, electric shovels | Separately excited, self excited differentially compound |

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# Graphical Flux Mapping

## I—Theory and General Discussion

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The purpose of these articles, of which this is the first, is to give a general theory for graphical flux mapping and to give a number of type cases and their application to problems in rotating electrical machines.

TO design and predict the performance of an electrical machine accurately it is very desirable to predetermine the true flux distribution. The correct calculation of the magnetizing current, of generated voltage, of reactance and of loss are all directly dependent on a rather exact knowledge of the magnetic field.

Certain of the methods which have been used in determining flux distribution may be summarized as follows:—

1—Flow analogies, such as current flow in templates or flow of colored liquids between plates.
2—Direct measurements on the magnetic field, such as could be made by a compass, a miniature armature, or iron filings placed in the field.
3—Mathematical analysis.
4—Graphical analysis.

All these methods have proven very satisfactory in certain cases, but at the present time it would seem that the graphical method has the greatest possibilities in the solution of engineering or design problems.

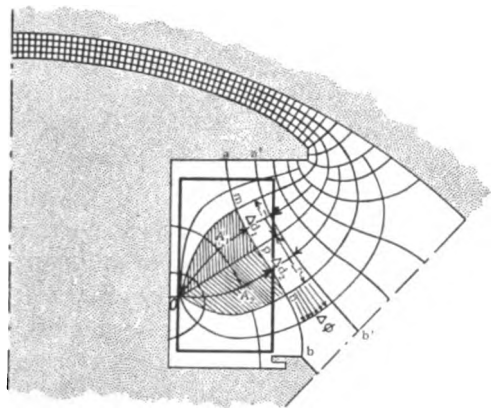

FIG. 1—A TYPICAL GRAPHICAL FLUX MAP
For a four pole, salient pole machine.

With the flow analogies, one encounters rather serious difficulty when the problem involves determining the distribution inside of a conductor. Direct measurements on the magnetic field have proven successful in most cases, but they are research rather than design methods. Explorations of this type are of great assistance when used in connection with the graphical method in obtaining qualitative ideas of the flux distribution. Mathematical solutions based upon the fundamental theories of flux distribution give the ultimately correct results. However, in most cases these are too complicated for daily use and in many cases the problems defy such solutions entirely.

In solving any problem graphically, the greatest assistance one can have is a drawing of a similar field. This suggests the possibility of establishing a number of type cases which would make the plotting of any particular field quite easy. Probably twenty or thirty fields would cover all the special types of problems which would be encountered in rotating apparatus. Therefore, it appears that the logical procedure is to project the work by establishing type cases graphically, and to have the results verified or corrected mathematically wherever possible.

### GENERAL THEORY OF GRAPHICAL FLUX MAPPING FOR NON-MAGNETIC PARTS

An electric current tends to establish a magnetic field of force around it in all planes at right angles to the direction of current flow. It has generally been found convenient to give arbitrary significances to the direction in which the force acts and its strength. The direction of the force is denoted by flux lines, and the density of these lines at any point is made proportional to the force in the direction of the lines. As there can be only one resultant direction of force at any point, then these resultant force lines do not cross, and must form closed loops about one or more magnetomotive force centers. The family of orthogonal lines at right angles to the force lines must converge at these centers, such as the point $O$ shown in Fig. 1.

In considering the flux distribution in non-magnetic parts it will be assumed first that the permeability of the iron is so much greater than the permeability of air that the iron may be regarded as a material of infinite permeability. Later, certain approximations will be made where it becomes desirable to consider the distribution in the iron parts.

It was stated above that the magnetomotive forces acted in such a way as to produce closed lines of force or flux about certain magnetomotive force centers. However, there is no force acting along any of the orthogonal lines and this fact may be used to establish a simple relation between the orthogonal lines and flux lines which will greatly assist in the plotting of these curves. Referring to Fig. 1, the following notation will be used:—

$AT_1$ and $AT_2$ = the ampere turns in the respective shaded areas $A_1$ and $A_2$ in Fig. 1.
$\Delta\phi$ = flux or number of lines of force going from $a$-$a'$ to $b$-$b'$. The number of lines is constant in value along this tube, and the tube is considered of negligible width so that there is no difference in the ampere turns acting on this circuit in the direction $ab$ and $a'b'$.
$l_1$ and $l_2$ = the lengths of the flux paths in the direction shown.
$\Delta d_1$ and $\Delta d_2$ = the corresponding mean widths.

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$H_1$ and $H_2$ = mean field intensities along $l_1$ and $l_2$ respectively.

The work done in moving a unit pole around the path *ompo* linking $AT_1$ is all done along *mp* or $l_1$. Similarly, in moving a unit pole around *opno* linking $AT_2$, the work is all done along *pn* or $l_2$.

Then $H_1 l_1 = 0.4\,\pi\,AT_1$ .....(1)
$H_2 l_2 = 0.4\,\pi\,AT_2$ .....(2)
and since $\Delta\phi = H_1 \Delta d_1 = H_2 \Delta d_2$ .....(3)
by substituting equation (3) in (1) and (2),—
$\Delta\phi(l_1/\Delta d_1) = 0.4\,\pi\,AT_1$ .....(4)
$\Delta\phi(l_2/\Delta d_2) = 0.4\,\pi\,AT_2$ .....(5)

Let $\Delta P_1$ and $\Delta P_2$ = the respective permeances in the two parts of the circuit shown above. Then,—
$\Delta P_1 = \Delta d_1/l_1$ .....(6)
$\Delta P_2 = \Delta d_2/l_2$ .....(7)

If uniform current densities are assumed, the ampere turns are proportional to $A_1$ and $A_2$ as follows:—

$$\frac{\Delta P_2}{\Delta P_1} = \frac{AT_1}{AT_2} = \frac{A_1}{A_2} \quad \text{.....(8)*}$$

Since all the ratios in this last equation can be estimated easily by eye, graphical solutions for the flux distribution can be made readily by simply attempting to draw the field and changing the figure until the relations expressed in eq. (8) are satisfied with a sufficient degree of accuracy. This is especially true where a similar solution is available for a guide.

## MAGNETIC PARTS ON THE BASIS OF UNIFORM PERMEABILITY

If the permeability of the flux path can be assumed constant, and if there is no change in flux ampere interlinkages between two flux tubes within the space under consideration, then a very simple extension of the preceding theory may be used in plotting the flux path in those parts external to the conductor. Let it be assumed

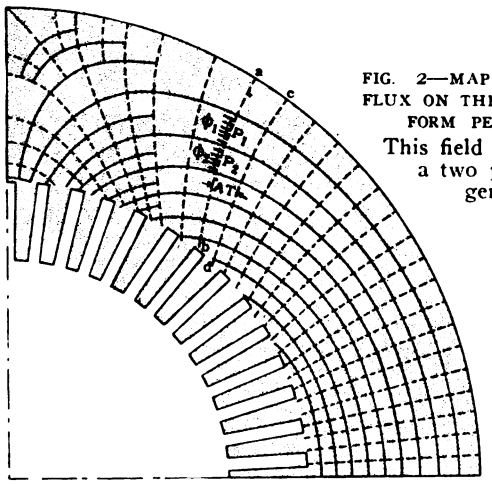


FIG. 2—MAP OF THE CORE FLUX ON THE BASIS OF UNIFORM PERMEABILITY
This field was drawn for a two pole turbine generator.

that the flux paths and orthogonal lines exist in some medium of uniform permeability, as shown in Fig. 2. Of the total magnetomotive force there is a certain fraction $AT$ acting between the lines *ab* and *cd*, as indicated in Fig. 2.

Then $\phi_1 = AT \times P_1$ .....(9)
$\phi_2 = AT \times P_2$ .....(10)
If $\phi_1 = \phi_2$ .....(11)
Then $P_1 = P_2$ .....(12)

*The above mathematical proof was made by Dr. J. Slepian.

In many cases the calculations on the air paths will give the flux entering the iron parts along various surfaces. The boundary conditions along all other surfaces can be determined but neither the flux distribution nor the magnetomotive force distribution can be determined alone. On the basis of uniform permeability

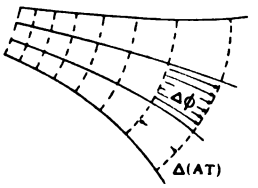


FIG. 3—A FLUX TUBE IN AIR OUTSIDE OF THE M.M.F. SOURCE

the flux distribution can be determined in accordance with eq. (9) to (12), by assuming equal flux tubes and equal ampere turn lines and closing the field within the boundaries with rectilinear squares. The flux distribution shown in Fig. 2 is for the core of a two-pole turbine generator, and was estimated on the basis of uniform iron permeability.

## GENERAL PROCEDURE FOR APPLICATION OF THEORY

Any scheme which gives a qualitative analysis is the first step in plotting a flux field. Usually it is best to establish the direction of the strongest part of the field first. If there is more than one source of m.m.f., it is advisable to draw in roughly the field due to each m.m.f. alone. When it is assumed that the iron is not saturated, either the flux or the ampere turns may be compounded in the non-magnetic parts. The flux components, each due to one m.m.f. acting alone, may be superposed to give a qualitative analysis which will show the general direction of the field. With this approximate solution in mind, it is possible to consider all the m.m.f.'s acting at one time.

It may be that the iron boundary conditions are too complicated or the m.m.f. sources too numerous to permit an immediate approximate visualization of the solution. In this case it is best to draw simplified boundary conditions and perhaps fewer m.m.f. sources. However, great care must be taken not to alter the premises of the case. In doing this the entire magnetic circuit should be considered, to avoid the possibility of any fundamental difference in the simplified case and real problem.

When the simplified case has been solved qualitatively, the complications of the real case may be added gradually until the qualitative solution for the true condition is obtained. When this is done all the m.m.f. sources should be considered. Almost always certain lines of symmetry may be found, and the distribution of the orthogonal lines may be established in certain parts. The relative number of orthogonal lines emanating from each m.m.f. center may be determined and these started outward from their respective sources. The remainder of the problem becomes one of extrapolation from the known parts of the field, and then of balancing the whole field so that it "closes" with rectilinear squares.

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As a rule, it is best to proceed with rather large sweeping curves at first, and to take care of the smaller divisions later. In this way the figure is first made to close approximately, and next to balance for correctness next. It is advisable to consider tubes of equal flux or

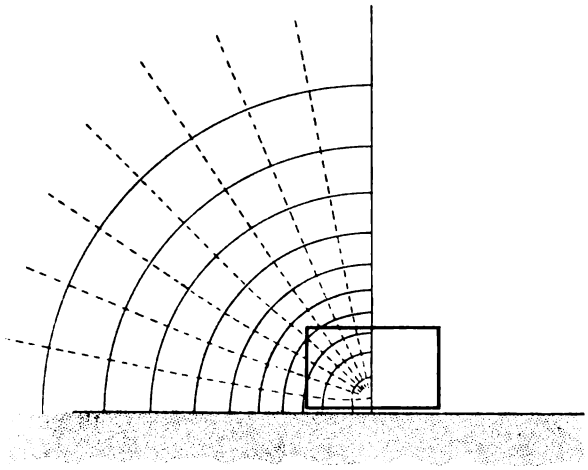

FIG. 4—THE FIELD OF A RECTANGULAR CONDUCTOR NEAR IRON

the following multiples;—¼, ½, 1, 2, 4, 8, 16, etc. Whenever a line is inserted to indicate a half a tube, a corresponding orthogonal line should be introduced. This is particularly useful outside of the m.m.f. source. The orthogonal lines and the flux tubes can be so chosen as to divide the space into parts of unit permeance outside of the m.m.f. source. If this is done there are three advantages:—

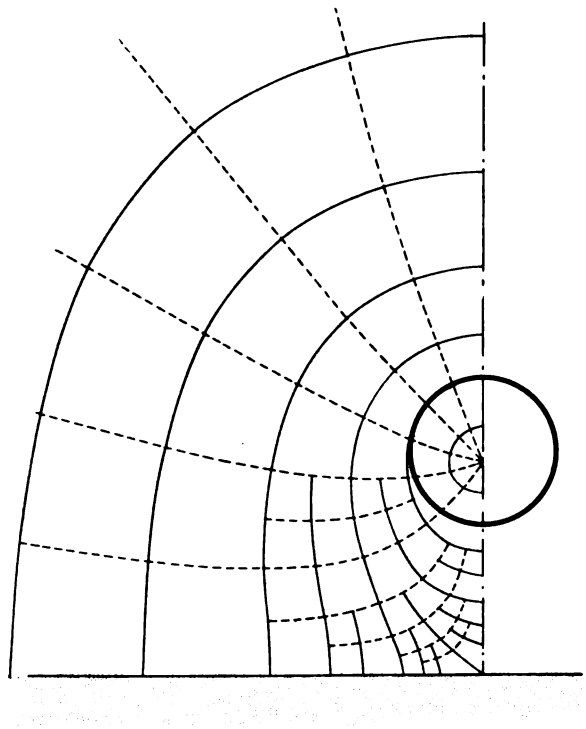

FIG. 5—THE FIELD OF A ROUND CONDUCTOR NEAR IRON

1—The accuracy of the field can be judged almost at a glance.

2—The number of flux tubes and multiples thereof can be counted directly without any confusion.

3—For one inch perpendicular to the sheet or plane of the drawing (if the conditions are assumed to be constant in that direction) the flux per tube may be determined in the non-magnetic parts from the following relation:—

$$\Delta\phi = 3.19\,\Delta(AT) \quad \ldots\ldots\ldots\ldots\ldots\ldots (13)$$

Where, $\Delta\phi$ = flux per tube.
$\Delta(AT)$ = ampere-turns required between two orthogonal lines, which cut out a space of unit permeance from the tube, as shown in Fig. 3.

FIELDS OF CONDUCTORS NEAR IRON

When a conductor carrying constant current is placed near iron, the magnetomotive force center will move toward the iron from that position which it would occupy if no iron were present. The exact position is that which will permit the greatest flux turn interlinkages per ampere when the fundamental principles of flux distribution are fulfilled. Figs. 4 and 5 illustrate fields which fulfill the above conditions. These fields were plotted by means of the principle relating the reluctance and ampere turns given in the theory of flux distributions in non-magnetic parts. Incidentally, Fig. 6 involves an application of Fig. 4, but it also shows the necessity of considering the whole magnetic circuit first.

In Fig. 4 the flux lines tend to become semicircular as the distance from the conductor increases. Equal ampere-turns will be required for approximately equal distances along the semicircular flux tubes. This gives

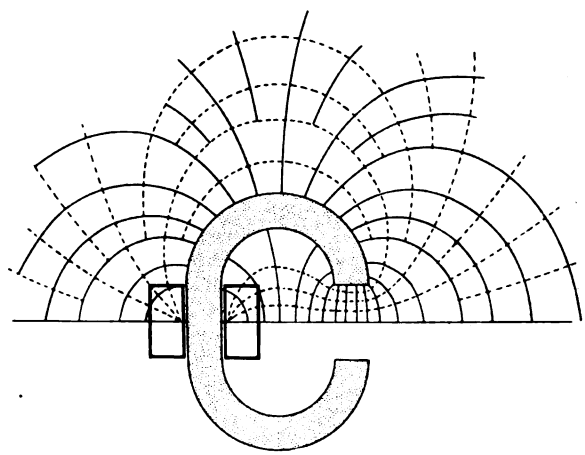

FIG. 6—THE FIELD OF AN ELECTRO-MAGNET
Illustrating an application of Fig. 4.

a condition of symmetry for use in the solution as indicated in the drawing.

Figure 5 affords the same conditions of symmetry for use in the solution of the outer portions of the field, but this principle is not useful between the conductor and the iron. One orthogonal line must go from the conductor to the iron. The construction required here has been described by Prof. A. D. Moore[6], and will be repeated here almost verbatim, because these principles which he gives are of use in solving one of the most common problems in graphical flux analysis, and because his explanation is particularly good. He first describes the flux distribution at an external corner and then at an internal corner. Although it is the internal corner principle which is of importance in Figs. 4 and 5, three of Prof. Moore's drawings showing these conditions will be given because they are of importance in explaining these and other figures.

"Referring to Fig. 7, there will be, by features of symmetry, a flux line *OM* that is straight; if projected

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into the body it will bisect the angle at the corner. The next feature peculiar about the case is another feature of symmetry; there will be a system of 'equipotential lines' (or 'orthogonal lines' as they have been called in this article) crossing this straight flux line normal to it; there will be a system of flux lines having the straight line BO normal to it; and these systems are

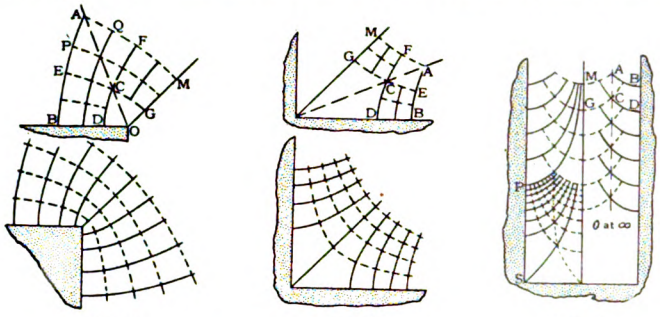

FIG. 7 FIG. 8 FIG. 9

FIG. 7—FLUX DISTRIBUTION AT AN EXTERNAL IRON CORNER
FIG. 8—FLUX DISTRIBUTION AT AN INTERNAL CORNER
FIG. 9—FLUX DISTRIBUTION AT THE INTERNAL CORNER AT THE BASE OF A SLOT

orthogonal. It is our right to guess, therefore, that the system in the region *BAMO* will be symmetrical about a construction bisector *OA* which bisects the angle *BOM*."

"It is obvious that, although the maps shown are not perfect, it is in theory possible to keep working at them until they are. Since under the conditions imposed either mathematical or physical law could put into the region only one set of lines and since the above method, in the limit, can meet the conditions imposed,

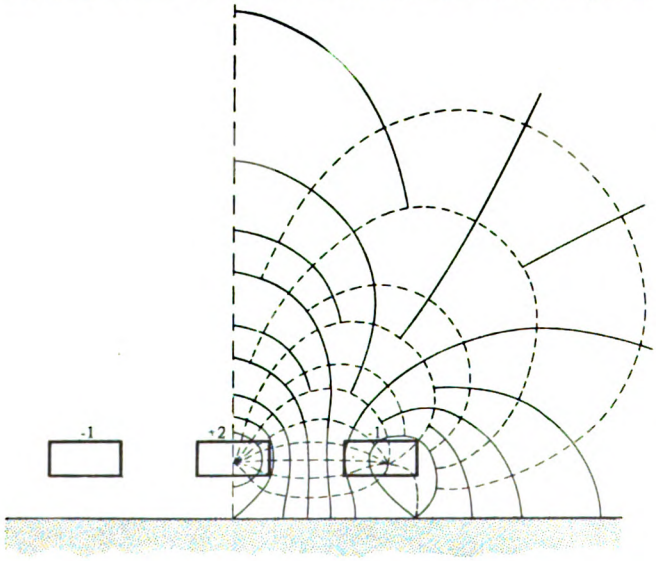


FIG. 10—THE FIELD OF THREE CONDUCTORS NEAR IRON
This distribution corresponds to one set of instantaneous values for a three-phase line.

the method must ultimately give the same results as could be obtained mathematically or physically."

"The same arguments apply to interior corners, as is brought out in Fig. 8. By symmetry, there will be a straight flux line *GM* bisecting the angle; the field will be symmetrical about the construction bisector *CA*."

An application of the interior "corner-flux principles" about the point *S* in the base of a slot is shown in Fig. 9. This figure also was taken from the article by Prof. Moore, and infinite permeability of the iron was assumed. On this basis the figure is correct.

To continue the discussion of the fields shown in Figs. 4 and 5, the most important difference is that in one case the space between the conductor and the iron is small and in the other case there is an appreciable space between the conductor and the iron, relative to the dimensions of the conductor.

A difficult type of field to plot is shown in Fig. 10. It is doubtful if such a resultant field has much practical application, because under alternating-current conditions the field would be continually changing in shape as well as in magnitude. Primarily, it is useful in visualizing the resultant flux conditions. It should be noticed that one orthogonal line from each conductor goes to the iron. All of the orthogonal lines from the right-hand conductor join with all of those from the right-hand half of the center conductor (for the values of current shown). The orthogonal line from the right-hand conductor which meets the iron is bowed away from the center conductor, and the magnetomotive force center of the right-hand conductor has (a) moved away from the center conductor, and (b) toward the iron, relative to the geometrical center of the right-hand conductor. The m.m.f. center of the right-hand conductor would correspond to its geometrical center, or mid-point, if it were acting alone in space. This position of the m.mf. center and of the orthogonal line which goes to the iron may be prophesied in a general way on the basis of the maximum flux-turn interlinkages per ampere. That is, the true field will have greater flux turn interlinkages than any other distribution which appears to fulfill the fundamental principles, but in which the errors cannot be clearly discerned.

*(To be Continued)*

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# Symmetrical Components

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THE solution of asymmetrical polyphase networks by the method of symmetrical components was discovered by Mr. C. L. Fortescue, the first publication appearing in 1918. Since then the method has been applied in the solution of a wide variety of engineering problems. It has been used most extensively in electrical engineering for the solution of problems involving unsymmetrical load or circuit conditions.

As an example of the applicability of this method consider the case of faults to ground on a power system. The ordinary methods of calculation, being based on symmetrical voltages and currents, are therefore limited to the case of the three-phase short-circuits, whereas it is probable that from 95 to 99 percent of all faults originate single-phase, either from line to ground or from line to line. The method of symmetrical components, however, is particularly well adapted to the calculation of single-phase faults. In fact it is the only practical method of determining the voltages and currents in the different phases in all parts of a power system, under conditions of single-phase load or short-circuit.

A knowledge of the method of symmetrical components is essential for an adequate understanding of application problems involving the magnitude and phase relation of voltages and currents under unbalanced conditions, and is therefore necessary for the design of power systems from the standpoint of circuit-breaker application, relay protection, and stresses in electrical machinery. The method is particularly suitable for the analysis of the performance of rotating machinery for single-phase or unbalanced polyphase operation, and has been used quite extensively in connection with the design of machinery on single-phase railway systems, particularly from the standpoint of phase-converting apparatus. A number of new schemes have appeared commercially which make use of conceptions arising from the method of symmetrical components, such as the negative-sequence protective relay and the positive-sequence voltage regulator. In recent years stability of power systems has been recognized as an important problem, and it has been shown that the limiting condition arises at times of faults, hence the method of symmetrical components has been of very considerable assistance in the analysis of stability problems.

The principles underlying the subject of symmetrical components were first presented in a paper by Mr. C. L. Fortescue before the American Institute of Electrical Engineers. Mr. Fortescue's treatment is quite general and thorough, and covers a large field in illustrating the application of the method to different types of problems. It necessitates, however, a familiarity with certain branches of higher mathematics which, through lack of application, the average engineer has forgotten. For this reason, and in response to repeated demands for a more popular presentation of the subject, the authors have undertaken this task.

The plan is to review briefly the laws governing complex numbers and then to develop certain theorems regarding the resolution of simple complex numbers into symmetrical groups. In particular these developments will apply largely to electrical systems involving symmetrical or balanced impedances. Illustrations of these theorems will be made by applying them to practical cases, such as the analysis of short-circuits in transmission networks. This will be followed by the application to a few miscellaneous problems, some of which will involve unsymmetrical impedances.

The treatment will be limited to three-phase systems only, except that the last article will develop some of the more important relations as applied to two or four-phase systems. The authors have drawn liberally from the unpublished as well as the published work of Messrs. Fortescue, Peters, and Slepian, and gratefully acknowledge the inspiration derived from personal contact with these men.

## LAWS OF COMPLEX NUMBERS

Any complex number, such as $a + jb$, may be represented by a single point plotted on Cartesian co-ordinates, in which $a$ is the abscissa and $b$ the ordinate. This is illustrated in Fig. 1. It is often convenient, however, to represent complex numbers by another method. Referring to Fig. 1, let $r$ represent the length of the line connecting the point with the origin and $\theta$ the angle measured from the $X$ axis to the line $r$. It is apparent that,—

$$a = r \cos \theta$$
$$b = r \sin \theta$$
$$\text{or } a + jb = r(\cos \theta + j \sin \theta) \quad \ldots\ldots (1)$$

This is called the polar form, in which $\theta$ is the argument or amplitude and $r$ the modulus or absolute value. Increasing $\theta$ in a positive sense rotates $OP$ counter clock-wise. Similarly,—

$$a - jb = r(\cos \theta - j \sin \theta) \quad \ldots\ldots (2)$$

Increasing $\theta$ in a positive sense in this case produces clock-wise rotation.

If $\epsilon^{\theta}$ be expanded into an infinite series,—

$$\epsilon^{\theta} = 1 + \theta + \frac{\theta^2}{2!} + \frac{\theta^3}{3!} + \frac{\theta^4}{4!} + \frac{\theta^5}{5!} + \frac{\theta^6}{6!} + \ldots\ldots$$

Similarly,—

$$\epsilon^{j\theta} = 1 + j\theta - \frac{\theta^2}{2!} - j\frac{\theta^3}{3!} + \frac{\theta^4}{4!} + j\frac{\theta^5}{5!} - \frac{\theta^6}{6!} \ldots\ldots$$

Separating the real and imaginary components,—

$$\epsilon^{j\theta} = \left(1 - \frac{\theta^2}{2!} + \frac{\theta^4}{4!} - \frac{\theta^6}{6!} + \ldots\ldots\right)$$
$$+ j\left(\theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} - \frac{\theta^7}{7!} + \ldots\ldots\right)$$

These expansions* are equal to cos $\theta$ and sin $\theta$ respectively, so that,—

*These relations may be verified by reference to any standard College Algebra.

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$$e^{j\theta} = \cos\theta + j\sin\theta \quad \ldots\ldots (3)$$

Similarly,—

$$e^{-j\theta} = \cos\theta - j\sin\theta \quad \ldots\ldots (4)$$

This suggests another form to represent a complex number. Substituting (3) in (1) and (4) in (2),—

$$a + jb = r e^{j\theta} \quad \ldots\ldots (5)$$

$$a - jb = r e^{-j\theta} \quad \ldots\ldots (6)$$

These forms will be found valuable for operations involving multiplication and division.

Returning to equations (1) and (2) and (5) and (6) it will be noted that the real components are equal, but that the imaginary components have opposite signs. These numbers are called conjugates.

In the notation used in this series of articles an ordinary complex number will be represented by placing the symbol v above the quantity, for example $\check{I}$. The conjugate will be designated by the inverse, $\hat{I}$. This notation may be easily remembered by associating the symbol with the first letter of the word vector.

If $\check{I} = a + jb$ the conjugate will be,—

$$\hat{I} = a - jb$$

The real and imaginary components may be expressed in terms of the complex number and its conjugate as follows:—

$$a = \frac{1}{2}(\check{I} + \hat{I}) \quad \ldots\ldots (7)$$

$$jb = \frac{1}{2}(\check{I} - \hat{I}) \quad \ldots\ldots (8)$$

The law for the addition of exponents holds equally well for both real and imaginary quantities. Just as $10^3 \times 10^4 = 10^7$ so,—

$$\epsilon^{j\theta_1} \times \epsilon^{j\theta_2} = \epsilon^{j(\theta_1 + \theta_2)}$$

from which it follows that the product of two complex numbers,—

$$\check{E} = E\,\epsilon^{j\theta_1} \text{ and } \check{I} = I\,\epsilon^{j\theta_2}$$

is equal to,—

$$\check{E}\check{I} = E\,I\,\epsilon^{j(\theta_1 + \theta_2)} \quad \ldots\ldots (9)$$

It will be noted that the absolute value of the product is the product of the absolute values of the components and that the argument is the sum of the arguments.

Multiplying by $e^{j\theta}$ merely rotates the modulus through an angle $\theta$ in a counter clock-wise direction. This point is important as it forms the basis for the proof of quite a number of circle diagrams.

If a complex number be multiplied by the conjugate of another, the argument of the product is the difference in arguments of the components.

$$\check{E}\hat{I} = E\,\epsilon^{j\theta_1} I\,\epsilon^{j-\theta_2} = E\,I\,\epsilon^{j(\theta_1 - \theta_2)} \quad \ldots\ldots (10)$$

Resolved into real and imaginary components,—

$$\check{E}\hat{I} = E\,I\,[\cos(\theta_1 - \theta_2) + j\sin(\theta_1 - \theta_2)] \quad \ldots\ldots (11)$$

Squaring a complex number merely increases the modulus as the square and rotates it through double the angle.

$$(I e^{j\theta})^2 = I^2 e^{j2\theta} \quad \ldots\ldots (12)$$

Division, the inverse of multiplication, can be accomplished in a similar manner.

$$\frac{\check{E}}{\check{I}} = \frac{E\,\epsilon^{j\theta_1}}{I\,\epsilon^{j\theta_2}} = \frac{E}{I}\,\epsilon^{j(\theta_1 - \theta_2)} \quad \ldots\ldots (13)$$

The absolute value of the resultant is equal to the quotient of the absolute values, and the argument is the difference of the arguments of the components.

As squaring a number merely increases the modulus to the square of the number and doubles the argument, extracting the square root, the inverse, is accomplished by taking the square root of the modulus and halving the argument. Generalizing, the modulus of the $n$th root of a number is the $n$th root of the modulus of the number and the argument is $\frac{1}{n}$ of the argument of the number.

$$\sqrt{I e^{j\theta}} = \sqrt[n]{I}\, e^{j\frac{\theta}{n}} \quad \ldots\ldots (14)$$

If a complex number be multiplied by its conjugate, the product is a real number of magnitude equal to the square of the absolute value of the number, for example.

$$\check{I}\hat{I} = I e^{j\theta} I e^{-j\theta} = I^2 e^{j(\theta - \theta)} = I^2 \quad \ldots\ldots (15)$$

## VECTOR REPRESENTATION OF ALTERNATING QUANTITIES

The instantaneous value of a simple harmonic function, such as an alternating electromotive force, may be represented by the following equation:—

$$e = \sqrt{2}E\cos(\omega t + \alpha)$$

where

$\omega = 2\pi f$

$f$ = frequency

$E$ = r.m.s. magnitude

$\sqrt{2}E$ = crest value

$\alpha$ = angle which determines the value of $e$ for $t = 0$.

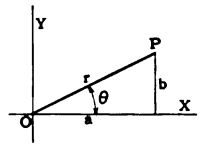


FIG. 1—A COMPLEX NUMBER

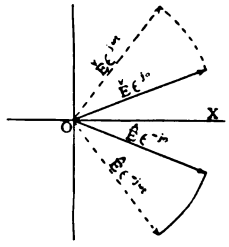


FIG. 2—A SIMPLE HARMONIC FUNCTION

By the addition of equations (3) and (4) it may be seen that $\cos\theta = \frac{1}{2}(\epsilon^{j\theta} + \epsilon^{-j\theta})$ and substituting $\omega t + \alpha$ for $\theta$, gives,—

$$\sqrt{2}E\cos(\omega t + \alpha) = \sqrt{2}E\left[\frac{e^{j(\omega t + \alpha)} + e^{-j(\omega t + \alpha)}}{2}\right] = \sqrt{2}E\left[\frac{e^{j\alpha}e^{j\omega t} + e^{-j\alpha}e^{-j\omega t}}{2}\right]$$

So that, if we let,—

$$\sqrt{2}E e^{j\alpha} = \sqrt{2}\check{E} \text{ and } \sqrt{2}E e^{-j\alpha} = \sqrt{2}\hat{E}$$

$$e = \frac{\sqrt{2}}{2}(\check{E} e^{j\omega t} + \hat{E} e^{-j\omega t}) \quad \ldots\ldots (16)$$

It will be noted from this equation that the instantaneous value can be represented as the sum of two oppositely rotating vectors which are conjugate at any instant, the imaginary components cancelling out. This relation is shown in Fig. 2, in which the full lines indicate the positions of $\check{E}$ and $\hat{E}$ for $t = 0$ and the dotted lines at an instant later. It will be noted that the two vectors are always symmetrically disposed relative to the $X$-axis so that their sum is always real and does not contain an imaginary component. Furthermore, the projection of either vector on the $X$-axis is always equal

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to one-half the sum of the vectors, and the instantaneous value can be represented by the real component of either vector. The same relations apply equally well to the instantaneous values of current.

### VECTOR REPRESENTATION OF POWER

By instantaneous power is meant the product of the instantaneous values of current and voltage. When the latter quantities vary in a sinusoidal manner, it may be shown that the expression for instantaneous power consists of a constant term with a sinusoidal term of double frequence superimposed. However, in most calculations one is interested only in the average value. It will be shown that this value can be determined in terms of the vector values of current and voltage in the form $\check{E}\hat{I}$ or $\hat{E}\check{I}$. These expressions are of particular value in analytical work, not only because they furnish a convenient expression for average power but because the imaginary component represents reactive power. To show these important relations let the instantaneous value of voltage be

$$e = \frac{\sqrt{2}}{2}(\check{E}\,\epsilon^{j\omega t} + \hat{E}\,\epsilon^{-j\omega t}) \quad \ldots\ldots (17)$$

and the instantaneous value of current be

$$i = \frac{\sqrt{2}}{2}(\check{I}\,\epsilon^{j\omega t} + \hat{I}\,\epsilon^{-j\omega t}) \quad \ldots\ldots (18)$$

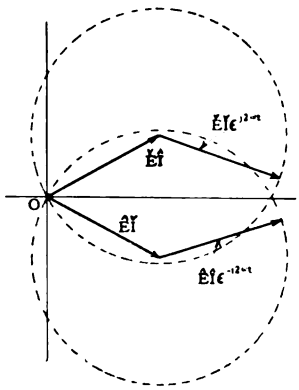


FIG. 3—DOUBLE-FREQUENCY ROTATING VECTORS

The instantaneous value of power is then

$$ei = \frac{(\check{E}\,\hat{I} + \check{E}\check{I}\,\epsilon^{j2\omega t})}{2} + \frac{(\hat{E}\check{I} + \hat{E}\,\hat{I}\,\epsilon^{-j2\omega t})}{2} \quad \ldots\ldots (19)$$

The two parts on the right hand side are conjugate to each other. $\check{E}\,\hat{I}$ and $\hat{E}\check{I}$ are conjugate vectors of equal magnitude independent of time, lying in opposite quadrants. The double frequency rotational vectors $\check{E}\check{I}\epsilon^{j2\omega t}$ and $\hat{E}\,\hat{I}\epsilon^{-j2\omega t}$ are also conjugate to each other and have the same absolute values as $\check{E}\hat{I}$ and $\hat{E}\check{I}$. These relations are illustrated in Fig. 3.

It can be seen that the average values of the double frequency components are zero so that the mean value of power $P$ is equal to $\frac{1}{2}(\check{E}\,\hat{I} + \hat{E}\check{I})$.

Now if $\check{E} = E\epsilon^{j\alpha}$ and $\check{I} = I\epsilon^{j\beta}$ then

$$\begin{aligned} P &= \frac{1}{2}\left[E\,I\,\epsilon^{j(\alpha-\beta)} + E\,I\,\epsilon^{-j(\alpha-\beta)}\right] \\ &= \frac{E\,I}{2}\Big[\left\{\cos(\alpha-\beta) + j\sin(\alpha-\beta)\right\} \\ &\quad + \left\{\cos(\alpha-\beta) - j\sin(\alpha-\beta)\right\}\Big] \\ &= E\,I\cos(\alpha-\beta) \quad \ldots\ldots (20) \end{aligned}$$

This is the familiar form of expression that is usually used. It will be observed that the real parts of both $\check{E}\,\hat{I}$ or $\hat{E}\check{I}$ are equal to this value and from this point of view, having once defined $P$ as the real part of $\check{E}\,\hat{I}$ or $\hat{E}\check{I}$, either expression can be used.

A rigorous proof for a similar relation for reactive power is quite involved, but starting with the definition of reactive power as equal to $E\,I\sin(\alpha-\beta)$ it is possible to show that the imaginary parts of the above expressions $\check{E}\,\hat{I}$ and $\hat{E}\check{I}$ equal the reactive power. To do this we must first define positive reactive power. Mr. Fortescue, in first presenting these forms, preferred to call reactive power positively when the current lags the voltage. This assumption immediately fixes the sense in which the angle $(\alpha-\beta)$ is measured, and determines that $(\alpha-\beta)$ shall be positive when the current lags the voltage, and negative when the current leads the voltage.

The imaginary component of $\check{E}\check{I}$ is $E\,I\sin(\alpha-\beta)$ but the imaginary component of $\check{E}\,\hat{I}$ is $-E\,I\sin(\alpha-\beta)$. The former is, therefore, of proper sign to conform with the original assumption of reactive power. Both real and reactive power may therefore be determined by the expression

$$P + jQ = \check{E}\,\hat{I} \quad \ldots\ldots (21)$$

However, had we started with the definition that positive reactive power conformed to leading current then we should have obtained the result

$$P + jQ = \hat{E}\check{I} \quad \ldots\ldots (22)$$

The choice of either expression is, therefore, dependent entirely upon the original assumption. It is important that, after having made a choice, one should be consistent throughout the particular problem. In these articles the expression $\check{E}\,\hat{I}$ will be used.

### RESOLUTION OF THREE VECTORS INTO SYMMETRICAL COMPONENTS

Any point on a line is completely defined by the distance from a given reference point, either in the positive direction or the negative. Similarly a point on a plane is completely defined by the distance from two reference axes and a point in space by the distance from three reference axes. A point on a line, being restrained to lie in the line, is said to possess but one degree of freedom; the point in the plane two degrees of freedom; and the point in space three degrees of freedom. So also with a co-planor vector, since it is determined by the position of its terminal it is said to possess two degrees of freedom.

Similar considerations apply to systems of vectors. For example, a system of three co-planar vectors is completely defined by six parameters; the system possesses six degrees of freedom. When, however, one applies the restriction that the system be symmetrical, the added restraint reduces the system to one of two degrees of freedom. Going a step further, it is quite conceivable that a system of three co-planar vectors with six degrees of freedom can be defined in terms of three symmetrical systems of vectors each having two degrees of freedom.

Consider first the symmetrical system of vectors $\check{E}_{a1}$, $\check{E}_{b1}$ and $\check{E}_{c1}$ in Fig. 4 (a). Being balanced, the vectors have equal amplitudes, are displaced 120 degrees relative to each other and,—

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$$\left.\begin{aligned} \check{E}_{a1} &= \check{E}_{a1} \\ \check{E}_{b1} &= e^{j240}\,\check{E}_{a1} = a^2\,\check{E}_{a1} \\ \check{E}_{c1} &= e^{j120}\,\check{E}_{a1} = a\,\check{E}_{a1} \end{aligned}\right\} \quad (23)$$

$$\left.\begin{aligned} &\text{in which } a \text{ is the unit vector, } e^{j120} = -0.5 + j\,0.866 \\ &\text{and } a^2 \text{ is the unit vector, } e^{j240} = -0.5 - j\,0.866 \end{aligned}\right\} \quad (24)$$

Because of the frequent use of this special vector the symbol denoting a vector will be omitted and this particular letter reserved for this use only. Some of the properties of this vector are given in Table I.

This system of vectors is called the positive sequence system, because $\check{E}_{a1}$ leads $\check{E}_{b1}$ by 120 degrees and $\check{E}_{b1}$ leads $\check{E}_{c1}$ by 120 degrees. Their instantaneous values pass through zero in the order $\check{E}_{a1}$, $\check{E}_{b1}$, $\check{E}_{c1}$. The system must always be treated as a unit. In a three-phase balanced electrical system $\check{E}_{a1}$ would represent the voltage of phase *A*; $a^2\,\check{E}_{a1}$ the voltage of phase *B*; and $a\,\check{E}_{a1}$ the voltage of phase *C*.

Likewise, consider the balanced system of vectors $\check{E}_{a2}$, $\check{E}_{b2}$, and $\check{E}_{c2}$ in Fig. 4 (b).

$$\left.\begin{aligned} \check{E}_{a2} &= \check{E}_{a2} \\ \check{E}_{b2} &= e^{j120}\,\check{E}_{a2} = a\,\check{E}_{a2} \\ \check{E}_{c2} &= e^{j240}\,\check{E}_{a2} = a^2\,\check{E}_{a2} \end{aligned}\right\} \quad (25)$$

This system of vectors is called the negative sequence system.

A physical picture of the significance of these systems may be obtained by considering the fields which result when voltages of the two systems are applied to the wind-

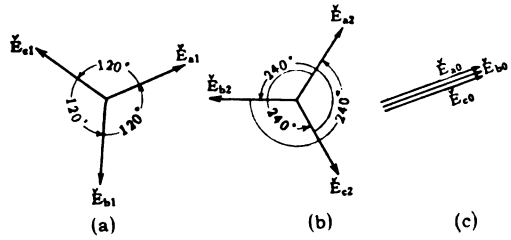


FIG. 4—VECTOR SYSTEMS

ings of a three-phase machine with distributed windings, such as an induction motor. If the *a*, *b*, and *c* phases of the positive sequence voltages be applied to the terminals *a*, *b*, *c*, respectively, a magnetic field will be produced which will revolve in a certain direction. If now the *a*, *b*, and *c* phases of the negative sequence voltages be connected to the *a*, *b*, and *c* terminals a magnetic field revolving in the opposite direction will be produced. This same effect may be produced by reversing one pair of leads but it will be noted that this in reality is the same as changing the phase sequence from *abc* to *acb* where the order indicates the order in which the different phases pass through zero.

Phase sequence should not be confused with the rotation of the vectors. In this series of articles the standard notion of counter-clockwise rotation will be accepted for all vectors; both positive and negative sequence vectors will rotate in the same direction but the resultant fields in machines will have opposite rotations.

And finally, consider the system $\check{E}_{a0}$, $\check{E}_{b0}$, and $\check{E}_{c0}$ in Fig. 4 (c) which represents three equal vectors.

$$\left.\begin{aligned} \check{E}_{a0} &= \check{E}_{a0} \\ \check{E}_{b0} &= \check{E}_{a0} \\ \check{E}_{c0} &= \check{E}_{a0} \end{aligned}\right\} \quad (26)$$

This system is called the zero sequence system.

In all three systems the suffixes denote the components of the respective systems in the different phases. The total voltage of any phase is then equal to the sum of the particular components of the different sequences in that phase. Therefore, any three arbitrary vectors $\check{E}_a$, $\check{E}_b$, and $\check{E}_c$ may be equated,—

$$\begin{aligned} \check{E}_a &= \check{E}_{a0} + \check{E}_{a1} + \check{E}_{a2} \\ \check{E}_b &= \check{E}_{b0} + \check{E}_{b1} + \check{E}_{b2} \\ \check{E}_c &= \check{E}_{c0} + \check{E}_{c1} + \check{E}_{c2} \end{aligned}$$

or substituting their equivalent values,—

$$\check{E}_a = \check{E}_{a0} + \check{E}_{a1} + \check{E}_{a2} \quad (27)$$

$$\check{E}_b = \check{E}_{a0} + a^2\,\check{E}_{a1} + a\,\check{E}_{a2} \quad (28)$$

$$\check{E}_c = \check{E}_{a0} + a\,\check{E}_{a1} + a^2\,\check{E}_{a2} \quad (29)$$

The arbitrary system is thus defined in terms of three balanced systems. The individual components may be obtained as follows:—

Adding the three equations, and recalling that $1 + a^2 + a = 0$

$$\check{E}_{a0} = \frac{\check{E}_a + \check{E}_b + \check{E}_c}{3} \quad (30)$$

Multiplying equation (28) by *a* and equation (29) by $a^2$ and adding,—

$$\check{E}_{a1} = \frac{\check{E}_a + a\,\check{E}_b + a^2\,\check{E}_c}{3} \quad (31)$$

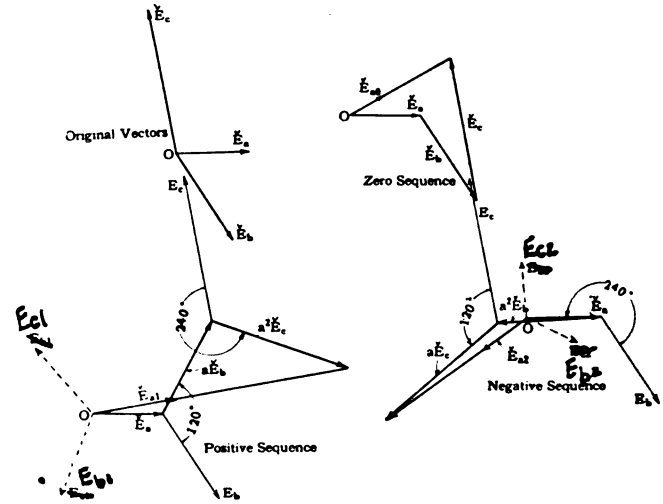


FIG. 5—GRAPHICAL CONSTRUCTION FOR THE DETERMINATION OF SEQUENCE COMPONENTS

Multiplying equation (28) by $a^2$ and equation (29) by *a* and adding,—

$$\check{E}_{a2} = \frac{\check{E}_a + a^2\,\check{E}_b + a\,\check{E}_c}{3} \quad (32)$$

Suppose the given voltages are balanced, for example,—

$$\begin{aligned} \check{E}_a &= \check{E}_a \\ \check{E}_b &= a^2\,\check{E}_a \\ \check{E}_c &= a\,\check{E}_a \end{aligned}$$

Then,—

$$\check{E}_{a0} = \frac{(1 + a^2 + a)}{3}\,\check{E}_a = 0$$

$$\check{E}_{a1} = \frac{(1 + a^3 + a^3)}{3}\,\check{E}_a = \check{E}_a$$

$$\check{E}_{a2} = \frac{1 + a^4 + a^2}{3}\,\check{E}_a = 0$$

The zero and negative sequence components of voltage in a balanced three-phase system disappear, leaving only the positive sequence.

The graphical construction for the determination of the sequence components will aid further in elucidating the operations. In Fig. 5 are shown three vectors,

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$\check{E}_a, \check{E}_b, \check{E}_c$. The zero sequence component $\check{E}_{a0}$ is obtained by direct addition. The positive sequence component $\check{E}_{a1}$ is obtained by rotating $\check{E}_b$ counter-clockwise 120 degrees, $\check{E}_c$ counter-clockwise 240 degrees, and taking one-third of the sum. Similarly $\check{E}_{a2}$ is determined by rotating $\check{E}_b$ clockwise 120 degrees, $\check{E}_c$ counter-clockwise 120 degrees, and taking one-third of the sum.

The method may be further illustrated by means of the analytical calculation of the components. Consider the three vectors,—

$$\check{E}_a = 60 + j\,0$$
$$\check{E}_b = 45 - j\,75$$
$$\check{E}_c = -21 + j\,120$$

From equations (30), (31) and (32),—

$$\check{E}_{a0} = \frac{1}{3}\left[\check{E}_a + \check{E}_b + \check{E}_c\right]$$
$$= \frac{1}{3}\Big[(60 + j\,0) + (45 - j\,75) + (-21 + j\,120)\Big]$$
$$= 28 + j\,15$$
$$\check{E}_{a1} = \frac{1}{3}\left[\check{E}_a + a\,\check{E}_b + a^2\,\check{E}_c\right]$$
$$= \frac{1}{3}\Big[(60 + j\,0) + (-0.5 + j\,0.866)(+45 - j\,75) + (-0.5 - j\,0.866)(-21 + j\,120)\Big]$$
$$= 72.2 + j\,11.5$$
$$\check{E}_{a2} = \frac{1}{3}\left[\check{E}_a + a^2\,\check{E}_b + a\,\check{E}_c\right]$$
$$= \frac{1}{3}\Big[(60 + j\,0) + (-0.5 - j\,0.866)(45 - j\,75) + (-0.5 + j\,0.866)(-21 + j\,120)\Big]$$
$$= -40.2 - j\,26.5$$

These three values give the symmetrical components of the three original vectors. Using these same values of components the determination of the original vectors in terms of their components may be illustrated.

From equations (27), (28) and (29),—

$$\check{E}_a = \check{E}_{a0} + \check{E}_{a1} + \check{E}_{a2}$$
$$= (28 + j\,15) + (-72.2 + j\,11.5) + (-40.2 - j\,26.5)$$
$$= 60 + j\,0$$
$$\check{E}_b = \check{E}_{a0} + a^2\,\check{E}_{a1} + a\,\check{E}_{a2}$$
$$= (28 + j\,15) + (-0.5 - j\,0.866)(72.2 + j\,11.5) + (-0.5 + j\,0.866)(-40.2 - j\,26.5)$$
$$= 45 - j\,75$$
$$\check{E}_c = \check{E}_{a0} + a\,\check{E}_{a1} + a^2\,\check{E}_{a2}$$
$$= (28 + j\,15) + (-0.5 + j\,0.866)(72.2 + 11.5) + (-0.5 - j\,0.866)(-40.2 - j\,26.5)$$
$$= -21 + j\,120$$

## SEQUENCE OPERATOR

Many mathematical operations may be designated by simplified notations, e.g. $\sqrt{\ }$ indicates that the square root of the number under the radical must be taken, $\frac{d}{dt}$ indicates that the function following should be differentiated with respect to time. These symbols are called operators and constitute shorthand methods of indicating certain mathematical operations. The $j$ in the complex algebra of alternating quantities may also be considered as an operator. It rotates the vector which is operated upon through 90 degrees. The operations in the three sequences may be indicated in a similar manner by means of the sequence operator. This operator is particularly useful for problems involving unsymmetrical impedances. Let $S^1$ $(\check{E}_{a1})$ represent the three vectors $\check{E}_{a1}$, $a^2\,\check{E}_{a1}$, $a\,\check{E}_{a1}$. $S^1$ may be considered as an operator affecting the three vectors $\check{E}_{a1}$, $\check{E}_{a1}$, $\check{E}_{a1}$, simultaneously by multiplying the first by 1, the second by $a^2$ and the third by $a$. It is an operator that can operate only on a polyphase system.

$S^2$ $(\check{E}_{a2})$ may represent the system of vectors, $\check{E}_{a2}$, $a\,\check{E}_{a2}$, $a^2\,\check{E}_{a2}$ and the operator $S^2$ shall be taken to mean that the polyphase vectors $\check{E}_{a2}$, $\check{E}_{a2}$, and $\check{E}_{a2}$ are multiplied respectively by 1, $a$ and $a^2$.

$S^0$ $(\check{E}_{a0})$ shall represent the system of vectors $\check{E}_{a0}$, $\check{E}_{a0}$, $\check{E}_{a0}$ and the operator $S^0$ the simultaneous multiplication of the three vectors $\check{E}_a$, $\check{E}_a$, and $\check{E}_a$ by unity.

So we may write,—

$$S^0\,(\check{E}_{a0}) = (1, 1, 1)\,\check{E}_{a0} \quad \text{.....(33)}$$
$$S^1\,(\check{E}_{a1}) = (1, a^2, a)\,\check{E}_{a1} \quad \text{.....(34)}$$
$$S^2\,(\check{E}_{a2}) = (1, a, a^2)\,\check{E}_{a2} \quad \text{.....(35)}$$

The system of vectors $\check{E}_a$, $\check{E}_b$ and $\check{E}_c$ in this notation is represented as follows:—

$$S\,(\check{E}_a) = S^0\,(\check{E}_{a0}) + S^1\,(\check{E}_{a1}) + S^2\,(\check{E}_{a2}) \quad \text{....(36)}$$

These operators possess interesting properties which when taken advantage of simplify analysis considerably.

*Addition and Subtraction.*—Two vectors operated on individually by a given sequence operator are equal to the sum of the vectors operated on by the sequence operator. For example:—

$$\left.\begin{aligned} S^1\,(\check{E}_a) + S^1(\check{E}_b) &= S^1\,(\check{E}_a + \check{E}_b) \\ S^0\,(\check{E}_a) + S^0\,(\check{E}_b) &= S^0\,(\check{E}_a + \check{E}_b) \\ S^1\,(\check{E}_a) - S^1\,(\check{E}_b) &= S^1\,(\check{E}_a - \check{E}_b) \end{aligned}\right\} \quad \text{.....(37)}$$

These relations are more or less evident. It should be noted, however, that the operators must be of the same phase sequence.

*Transfer of Vector Multiplier.*—A vector multiplier may be transferred from outside the vector operator to the inside.

$$K\,S^1\,(\check{E}) = S^1\,(K\,\check{E}) \quad \text{.....(38)}$$

*Multiplication of Sequence Operators.*—The exponents of the sequence operators follow the law of the exponents of $a$ in multiplication. $(a \times a = a^2;\ a^2 \times a = a^3 = 1)$.

$$S^1\,(\check{E}) \times S^1\,(\check{I}) = S^2\,(\check{E}\,\check{I})$$

Before considering this statement it is necessary to state just what is meant by this type of multiplication. $S^1$ $(\check{E})$ and $S^1$ $(\check{I})$ each consist of three terms. The multiplication will be assumed to occur symmetrically, the first terms, the second terms and third terms of the groups being multiplied respectively. There is no cross multiplication because each term represents a separate vector. Then,—

$$S^1\,(\check{E}) \times S^1\,(\check{I}) = (\check{E}, a^2\,\check{E}, a\,\check{E}) \times (\check{I}, a^2\,\check{I}, a\,\check{I})$$
$$\check{E} \text{ multiplied by } \check{I} = \check{E}\,\check{I}$$
$$a^2\,\check{E} \text{ multiplied by } a^2\,\check{I} = a^4\,\check{E}\,\check{I} = a\,\check{E}\,\check{I}$$
$$a\,\check{E} \text{ multiplied by } a\,\check{I} = a^2\,\check{E}\,\check{I}$$

So that the product is,—

$$(\check{E}\,\check{I}, a\,\check{E}\,\check{I}, a^2\,\check{E}\,\check{I})$$

which is equal to,—

$$(1, a, a^2)\,\check{E}\,\check{I} = S^2\,(\check{E}\,\check{I})$$

Similarly,—

$$S^2\,(\check{E}) \times S^2\,(\check{I}) = (1, a, a^2)\,\check{E} \times (1, a, a^2)\,\check{I}$$
$$= (1, a^2, a)\,\check{E}\,\check{I}$$
$$= S^1\,(\check{E}\,\check{I})$$

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It is evident that adding the exponents (2 + 2) produces 4. This result is similar to that produced by $a^2 \times a^2 = a^4 = a$. The same law also prevails in the application to the sequence operators. This may be further illustrated by,—

$$S^2(\check{E}) \times S^1(\check{I}) = (1, a^2, a)\,\check{E} \times (1, a, a^2)\,\check{I}$$
$$= (1, 1, 1)\,\check{E}\,\check{I}$$
$$= S^0(\check{E}\,\check{I})$$

This relation may be generalized into,—

$$S^m(\check{E}) \times S^n(\check{I}) = S^{m+n}(\check{E}\,\check{I}) \quad \text{.....(39)}$$

Just as $\frac{d}{dt}$, $\sqrt{}$, *sin*, etc., by themselves mean nothing and only take on significance when followed by a function of some kind, so $S^0$, $S^1$, and $S^2$ by themselves mean nothing. When it is desired to express the three vectors 1, $a^2$, $a$, the operator must be followed by unity, e.g. $S^1(1)$.

TABLE I—PROPERTIES OF THE VECTOR $a$

| | |
|---|---|
| $1 = e^{j0} = 1.0 + j\,0.0$ | $1 + a^2 + a = 0$ |
| $a = e^{j120} = -0.5 + j\,0.866$ | $a - a^2 = \sqrt{3}\,e^{j90} = j\sqrt{3}$ |
| $a^2 = e^{j240} = -0.5 - j\,0.866$ | $a^2 - a = \sqrt{3}\,e^{-j90} = -j\sqrt{3}$ |
| $a^3 = e^{j360} = e^{j0} = 1.0 + j\,0.0$ | $1 - a = \sqrt{3}\,e^{-j30} = 1.5 - j\,0.866$ |
| $a^4 = e^{j480} = e^{j120}$ | $1 - a^2 = \sqrt{3}\,e^{j30} = 1.5 + j\,0.866$ |
| $a^5 = e^{j600} = e^{j240}$ | |

CHANGE OF FIRST TERM IN SEQUENCE

In all of the discussion so far phase $A$ has been used as the reference phase the first term in the sequence. The notation

$$S(\check{E}_a) = S^0\,\check{E}_{a0} + S^1\,\check{E}_{a1} + S^2\,\check{E}_{a2}$$

means that $\check{E}_a$ is the first term in the sequence. It sometimes becomes desirable to change the first term. Instead of considering the vectors $\check{E}_a$, $\check{E}_b$, $\check{E}_c$, one might wish to consider them in the order $\check{E}_b$, $\check{E}_c$, $\check{E}_a$. This can be accomplished as follows:

Using phase $A$ as datum:

$$\check{E}_{a0} = 1/3\,(\check{E}_a + \check{E}_b + \check{E}_c)$$
$$\check{E}_{a1} = 1/3\,(\check{E}_a + a\,\check{E}_b + a^2\,\check{E}_c)$$
$$\check{E}_{a2} = 1/3\,(\check{E}_a + a^2\,\check{E}_b + a\,\check{E}_c)$$

Using phase $B$ as datum:

$$\left.\begin{aligned}
\check{E}_{b0} &= 1/3\,(\check{E}_b + \check{E}_c + \check{E}_a) = \check{E}_{a0} \\
\check{E}_{b1} &= 1/3\,(\check{E}_b + a\,\check{E}_c + a^2\,\check{E}_a) \\
&= a^2\,1/3\,(a\,\check{E}_b + a^2\,\check{E}_c + \check{E}_a) = a^2\,\check{E}_{a1} \\
\check{E}_{b2} &= 1/3\,(\check{E}_b + a^2\,\check{E}_c + a\,\check{E}_a) \\
&= a\,1/3\,(a^2\,\check{E}_b + a\,\check{E}_c + \check{E}_a) = a\,\check{E}_{a2}
\end{aligned}\right\} \quad \text{.....(40)}$$

Using phase $C$ as datum:

$$\left.\begin{aligned}
\check{E}_{c0} &= 1/3\,(\check{E}_c + \check{E}_a + \check{E}_b) = \check{E}_{a0} \\
\check{E}_{c1} &= 1/3\,(\check{E}_c + a\,\check{E}_a + a^2\,\check{E}_b) \\
&= 1/3\,(a^2\,\check{E}_c + \check{E}_a + a\,\check{E}_b) = a\,\check{E}_{a1} \\
\check{E}_{c2} &= 1/3\,(\check{E}_c + a^2\,\check{E}_a + a\,\check{E}_b) \\
&= a^2\,1/3\,(a\,\check{E}_c + \check{E}_a + a^2\,\check{E}_b) = a^2\,\check{E}_{a2}
\end{aligned}\right\} \quad \text{.....(41)}$$

Now since

$$S(\check{E}_b) = S^0\,\check{E}_{b0} + S^1\,\check{E}_{b1} + S^2\,\check{E}_{b2} \quad \text{..... (42)}$$

and

$$S(\check{E}_c) = S^0\,\check{E}_{c0} + S^1\,\check{E}_{c1} + S^2\,\check{E}_{c2} \quad \text{..... (43)}$$

Substitutiug the above values of components, we obtain:

$$S(\check{E}_b) = S^0\,\check{E}_{a0} + S^1\,a^2\,\check{E}_{a1} + S^2\,a\,\check{E}_{a2} \quad \text{..... (44)}$$
$$S(\check{E}_c) = S^0\,\check{E}_{a0} + S^1\,a\,\check{E}_{a1} + S^2\,a^2\,\check{E}_{a2} \quad \text{..... (45)}$$

Equation (42) expresses the three vectors $\check{E}_b$, $\check{E}_c$, and $\check{E}_a$ in terms of the components, using $\check{E}_b$, as the first term or datum, while equation (44) expresses the same vectors in terms of the sequence components using $\check{E}_a$ as the first term. Similarly equations (43) and (45) express the three vectors $\check{E}_c$, $\check{E}_a$, $\check{E}_b$, in terms of their sequence components using $\check{E}_c$ and $\check{E}_a$, respectively as the first term.

STAR-DELTA TRANSFORMATIONS

Problems sometimes arise involving both star and delta currents and voltages. The conditions are such that the equations are set up more easily in terms of both star and delta quantities. It is convenient for the solution of such problems to be able to convert readily from star to delta and vice-versa in terms of the symmetrical components.

Let $\check{I}_A$, $\check{I}_B$, and $\check{I}_C$, be the delta currents in the delta connected windings of a machine and $\check{I}_a$, $\check{I}_b$, and $\check{I}_c$, the currents in the line in Fig. 6. In terms of their sequence components the two systems may be expressed as follows:

$$S(\check{I}_A) = S^0\,\check{I}_{A0} + S^1\,\check{I}_{A1} + S^2\,\check{I}_{A2} \quad \text{..... (46)}$$
$$S(\check{I}_a) = S^0\,\check{I}_{a0} + S^1\,\check{I}_{a1} + S^2\,\check{I}_{a2} \quad \text{..... (47)}$$

At the junctions the following relations are satisfied:

$$\check{I}_a = \check{I}_B - \check{I}_C$$
$$\check{I}_b = \check{I}_C - \check{I}_A$$
$$\check{I}_c = \check{I}_A - \check{I}_B$$

or

$$S(\check{I}_a) = S(\check{I}_B) - S(\check{I}_C) \quad \text{..... (48)}$$

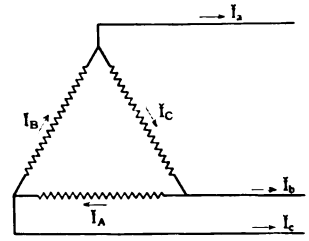


FIG. 6—CURRENTS IN A DELTA-CONNECTED SYSTEM

Using the relations from equations (46) and (47) the first terms in the last two expressions may be changed, so that on substituting the values of $S(\check{I}_A)$ and $S(\check{I}_a)$ from equations (46) and (47), equation (48) becomes:

$$S^0\,\check{I}_{a0} + S^1\,\check{I}_{a1} + S^2\,\check{I}_{a2}$$
$$= S^0\,\check{I}_{A0} + S^1\,a^2\,\check{I}_{A1} + S^2\,a\,\check{I}_{A2}$$
$$- S^0\,\check{I}_{A0} - S^1\,a\,\check{I}_{A1} - S^2\,a^2\,\check{I}_{A2}$$

From which

$$S^0\,\check{I}_{a0} = S^0(\check{I}_{A0} - \check{I}_{A0}) = 0$$
$$S^1\,\check{I}_{a1} = S^1(a^2 - a)\,\check{I}_{A1} = S^1(-j\sqrt{3})\,\check{I}_{A1}$$
$$S^2\,\check{I}_{a2} = S^2(a - a^2)\,\check{I}_{A2} = S^2(+j\sqrt{3})\,\check{I}_{A2}$$

or

$$\left.\begin{aligned}
\check{I}_{a0} &= 0 & \check{I}_{A0} &= \textit{indeterminant} \\
\check{I}_{a1} &= -j\sqrt{3}\,\check{I}_{A1} & \check{I}_{A1} &= \frac{j}{\sqrt{3}}\,\check{I}_{a1} \\
\check{I}_{a2} &= +j\sqrt{3}\,\check{I}_{A2} & \check{I}_{A2} &= \frac{j}{\sqrt{3}}\,\check{I}_{a2}
\end{aligned}\right\} \quad \text{.....(49)}$$

These relations are indicated in the vector diagram, Fig. 7.

It is apparent that no zero sequence current can exist in lines feeding a delta connection, and that currents of zero sequence circulating in the delta are indeterminant from line currents alone.

Now let $\check{E}_A$, $\check{E}_B$, and $\check{E}_C$, (Fig. 8), be the delta voltages and $\check{E}_a$, $\check{E}_b$, and $\check{E}_c$, the star voltages. What are the corresponding equivalences as obtained for currents?

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In terms of their sequence components the two systems may be expressed as follows:

$$S(\check{E}_a) = S^0 \check{E}_{a0} + S^1 \check{E}_{a1} + S^2 \check{E}_{a2} \quad \ldots\ldots (50)$$

$$S(\check{E}_A) = S^0 \check{E}_{A0} + S^1 \check{E}_{A1} + S^2 \check{E}_{A2} \quad \ldots\ldots (51)$$

By definition let

$$\check{E}_A = \check{E}_c - \check{E}_b$$
$$\check{E}_B = \check{E}_a - \check{E}_c$$
$$\check{E}_C = \check{E}_b - \check{E}_a$$

(With equal justification we could have assumed $\check{E}_a = \check{e}_b - \check{e}_c$, etc. The choice is purely arbitrary.)

$$S^0 \check{E}_{A0} + S^1 \check{E}_{A1} + S^2 \check{E}_{A2} = S^0 \check{E}_{a0} + S^1 a \check{E}_{a1} + S^2 a^2 \check{E}_{a2} - S^0 \check{E}_{a0} - S^1 a^2 \check{E}_{a1} - S^2 a \check{E}_{a2}$$

From which

$$S^0 \check{E}_{A0} = S^0 (\check{E}_{a0} - \check{E}_{a0}) = 0$$
$$S^1 \check{E}_{A1} = S^1 (a - a^2) \check{E}_{a1} = S^1 (+j\sqrt{3}) \check{E}_{a1}$$
$$S^2 \check{E}_{A2} = S^2 (a^2 - a) \check{E}_{a2} = S^2 (-j\sqrt{3}) \check{E}_{a2}$$

$$\left.\begin{array}{ll} \check{E}_{a0} = \textit{indeterminant} & \check{E}_{A0} = 0 \\ \check{E}_{a1} = -\dfrac{j}{\sqrt{3}} \check{E}_{A1} & \check{E}_{A1} = (j\sqrt{3}) \check{E}_{a1} \\ \check{E}_{a2} = +\dfrac{j}{\sqrt{3}} \check{E}_{A2} & \check{E}_{A2} = (-j\sqrt{3}) \check{E}_{a2} \end{array}\right\} \quad \ldots\ldots (53)$$

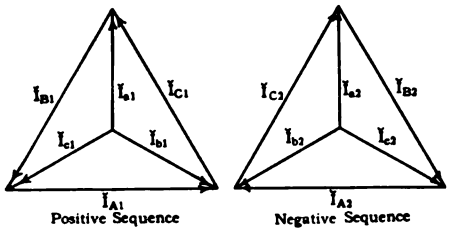


FIG. 7—CURRENT RELATIONSHIPS

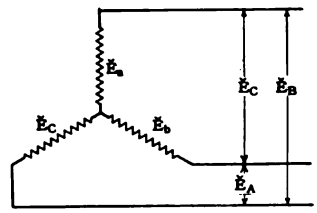


FIG. 8—VOLTAGES IN A STAR-CONNECTED SYSTEM

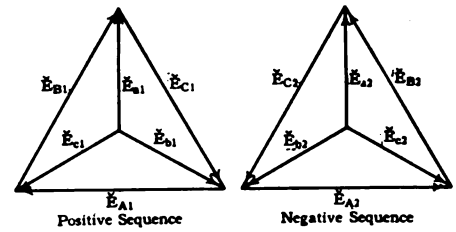


FIG. 9—VOLTAGE RELATIONSHIP

or

$$S(\check{E}_A) = S(\check{E}_c) - S(\check{E}_b) \quad \ldots\ldots (52)$$

Changing the first term in the last two expressions and substituting we obtain:

These relations are indicated in the vector diagram in Fig. 9. Because the sum of the delta voltage must always form a closed triangle, i. e., add to zero, the delta voltages can contain no zero sequence quantity.

# A New Resistor for Use in Measurements of Impulse Voltages and Currents

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Supply Engineer,
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PURE resistances are necessary accessories for circuits used in making tests with impulse voltages. They are used to limit currents; as shunts for measuring current by means of sphere gaps, klydonographs or oscillographs; and as potentiometers for measuring voltage, particularly in investigations conducted by means of artificial lightning generators. These resistors should be constant over their entire voltage range; the rate of change of current should not effect the resistance—in other words it is desirable that the skin effect be negligible. They should be convenient to handle, and not subject to changes with time or atmospheric conditions.

Heretofore the only type of resistance which has approached this ideal has been a water resistance. This, however, has the disadvantage of being troublesome to handle and subject to change with time. Wire resistances show pronounced skin effect unless specially constructed.

The most convenient resistor to handle is a ceramic composition rod. High resistances can be made using material of fairly high resistivity, reducing the skin effect to a minimum. The composition rods heretofore available are not suitable for impulse circuits, however, because their resistance varies with the applied voltage, decreasing as the voltage increases. This is due to the nature of the component materials.

Another fault of the common composition resistors is introduced by the method of manufacture. They are usually made by squirting the material through a die and cutting it off into the desired lengths, after which the rods thus obtained are baked. This produces an inhomogeneous piece. Rods of this kind may have laminations running across the current carrying axis. They usually have sections which are of greater conductivity than others. They are therefore unreliable, subject to

FIG. 1—APPEARANCE OF A ZIRCON RESISTOR WITH A NON-INDUCTIVE RESISTANCE OF 150 OHMS

flashover on high voltage, and comparatively weak mechanically.

To overcome these faults, particularly the obnoxious characteristic of decreasing resistance with increasing voltage, a new composition was sought. It was found in the so-called zircon mixture. The rods which have been made of this material are not extruded, but moulded with the pressure applied perpendicularly to the current carrying axis. By this means a mechanically strong and electrically uniform rod is obtained. If any

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laminations do exist, they are harmless because as they are parallel to the current carrying path they do not affect the resistance of the rod.

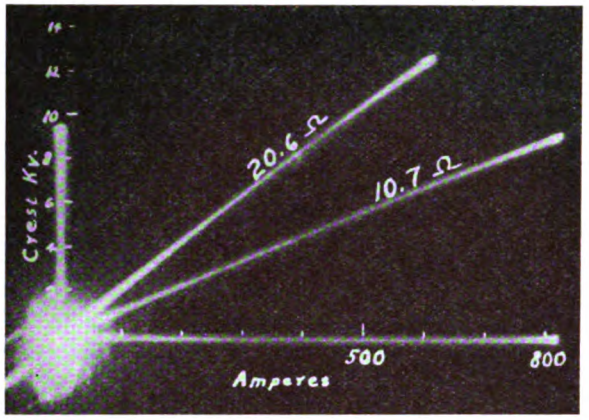


FIG. 2—VOLT-AMPERE CHARACTERISTICS OF TWO ZIRCON RODS OF 10.7 AND 20.6 OHMS AS OBTAINED ON A DUFOUR OSCILLOGRAPH

The behavior of these rods when subjected to lightning discharges is beautifully demonstrated by means of the Du Four high-speed cathode-ray oscillograph. Fig. 2 shows the volt-ampere characteristics of two zircon

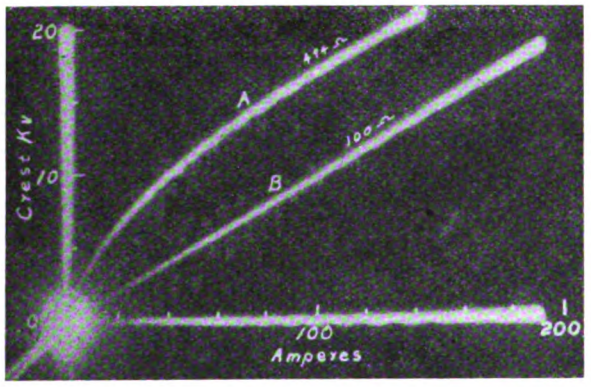


FIG. 3—COMPARISON OF ZIRCON AND ORDINARY COMPOSITION RESISTOR UNITS

rods of different compositions. Impulses were impressed by a lightning generator delivering a voltage whose rate of rise is 50 000 volts per microsecond. The voltage across the rod and the current through it are measured

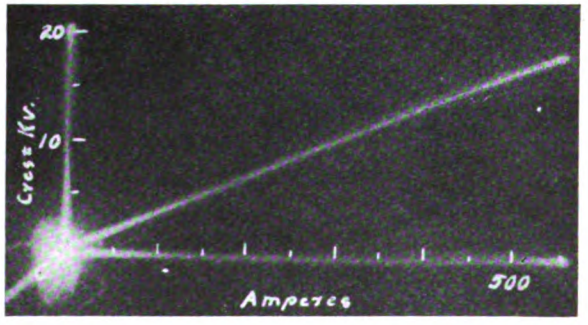


FIG. 4—CHARACTERISTICS OF A HIGH RESISTANCE WATER RHEOSTAT

simultaneously by the Du Four oscillograph. The characteristics are straight lines passing through the origin, indicating constant resistance with varying voltage. The resistances as derived from these characteristics check closely with those measured by a Wheatstone bridge.

A similar oscillogram in Fig. 3 shows the behavior of a zircon rod of higher resistance at *B*, together with the characteristics of one of the common resistors at *A*. The drooping of *A* plainly shows why the ordinary composition rod is not suitable for impulse measurements.

As a further check on the suitability of the zircon rods for impulse and high frequency measurements, the resistance of a number of rods was measured at 1 000 000 cycles. It was found that the deviation from the resistance as measured with a Wheatstone bridge was only two percent. The high-frequency resistance was not greater than the direct-current resistance but less, a rather surprising discovery. The reduced resistance at high frequency is probably due to a small capacitive current which flows through the rod by means of the electrostatic capacity between the particles of conducting carbon. For comparison, the characteristic of a water resistance is shown in Fig. 4.

The nature of the zircon rods makes them particularly suitable for field investigations of lightning dis-

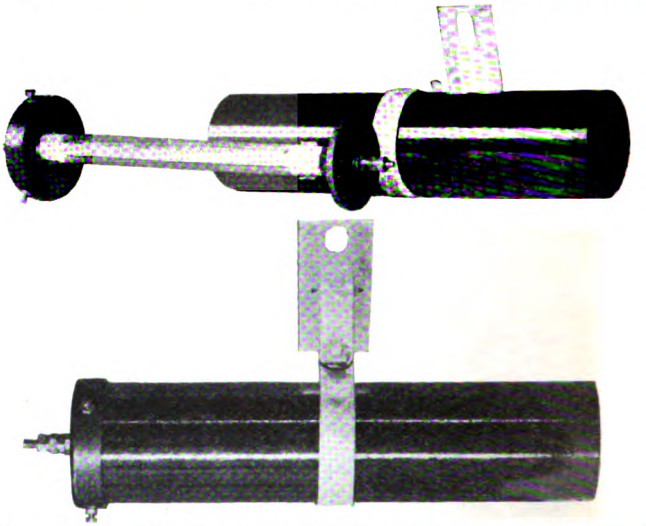

FIG. 5—DISASSEMBLED AND ASSEMBLED VIEWS OF A ZIRCON CURRENT-SHUNT FOR A KLYDONOGRAPH

turbances on transmission lines. Fig. 5 shows a current shunt for a klydonograph used in measuring the transient currents discharged by lightning arrestors in service. Heretofore, it has been necessary to use water tube or wire resistances, both of which are inconvenient. The zircon rod has made possible a convenient and accurate device for this service.

Rods of this kind have been in use in the laboratory and in the field for over a year in the investigation of transient phenomena. They have shown no measurable change in characteristics. Tests made on klydonograph shunts of this material indicated exactly the same resistance on a Wheatstone bridge and the same behavior on surge voltages after a season of service as when new.

These resistors, developed by G. F. Harrington, have simplified the manipulation of circuits used in impulse testing or measuring. Their application is not limited to the one above described, but the behavior of these rods on impulse voltages serves most strikingly to point out the electrical superiority of the zircon rod.

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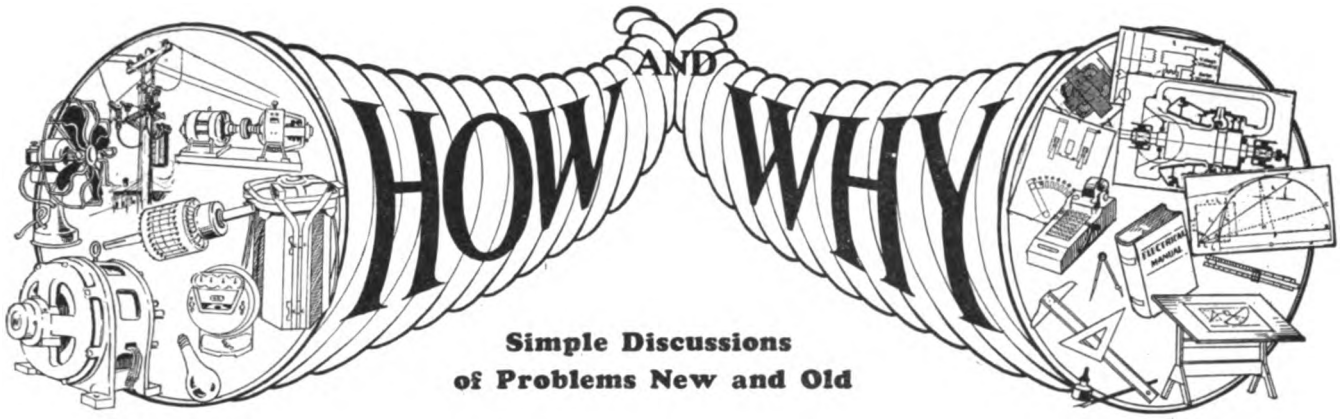


## A New Army Mule

THE U. S. Army is testing a new kind of mule which is considerably more sturdy and serviceable (and much less stubborn) than the mule of previous days. This new, mechanical mule with its motor-driven six wheels and truck body looks like a cross between a motor coach and a truck. However, it belies its looks, for it can serve a variety of purposes that would put the old, reliable army mule to shame. By simply replacing the quickly detachable truck body shown in Fig. 1 with one of several other kinds, the truck can do duty as a field machine shop, as a hospital unit, as a photograph developing plant, as a truck for hauling men or supplies, as a flat bed for gun mounts or for aeroplane carrying. Then when it hasn't anything else to do, its electric generator can be used to furnish power for search lights, for field camp lighting, for machine shop tools or for various other electrical equipments.

Power for the truck is supplied by a six-cylinder, 125 horse-power gas engine driving a 40 kw. 200 volt, 1200 r.p.m. direct-current generator. The generator is a commutating-pole machine of special design, with a teaser field winding

FIG. 1—AN ELECTRICALLY DRIVEN MULTI-PURPOSE ARMY TRUCK

supplied from a battery to furnish a constant small amount of excitation. This insures a rapid pick up and stable operation under all conditions.

The truck is driven by three motors, one mounted on each axle. These are dual-ventilated, series motors, with commutating poles, and rated at 27.5 h.p., 250 volts. The excess of motor over generator horse-power is due to the motors being built for regenerative braking. The three motors drive the wheels through 9.4 to 1 reduction gears, the front axle being provided with a special kind of hub to prevent the transmission of power from affecting the ease of steering.

The motors are controlled by a drum-type controller mounted close to the driver. It provides for either series or parallel operation as required to supply the tractive effort necessary at different loads.

Like the mule this new truck replaces, it is well supplied with braking power. When descending long grades or when decelerating, braking force is supplied by dissipating in grid resistors regeneration energy from two of the motors. Pneumatic brakes and hand-operated friction brakes are also provided on the rear wheels.

The wide range of flexibility of the unit is illustrated by the voltage control of the generator. When being used as a truck the voltage supplied to the motors varies from zero to about 400 volts. However, when the generator is used to supply power for various electrical equipment, close regulation to 125 volts is desired. This is accomplished by a relay which automatically inserts or cuts out resistance from the main field of the generator as the load and engine speed vary.

This all-purpose truck is still in the experimental stage but public demonstrations have shown it to be a worthy successor to the army mule.

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## Why the Lights Wink

WHY the lights on a small direct-current system flicker as the load changes is not always clearly understood. As a result, caustic remarks are sometimes made about the power system, or company or generators or anything else that comes to mind when in reality the fault is one common to all systems as will be seen from an explanation of the flicker.

When a load is added to a system there is a drop in voltage, giving an apparent wink of the lamps, which may have several causes. There is a small permanent decrease in voltage due to increased line drop. Sometimes the added load may be of such a nature, as a motor, as to take a high current for just an instant or two. During this peak, the line drop is greater and the voltage across lamps connected to it lower. Then, in addition, there is a momentary voltage dip resulting from the addition of any load.

To demonstrate the latter, assume that we have a 100-volt generator supplying a load of 100 amperes; the resistance of the load is therefore one ohm. Suppose that we suddenly connect another resistance of one ohm in parallel with the load, as in Fig. 1. According to Ohm's law of resistances in parallel, the circuit resistance immediately becomes one-half ohm. At this instant the current is still 100 amperes. The line drop is therefore $1/2 \times 100 = 50$ volts; the generated voltage remains 100. This difference of 50 volts results, of course, in a very rapid rise in generated current—to 200 amperes. The rise, however, because of the self-inductance of the generator, cannot be instantaneous; instead, the current builds up along the well-known logarithmic curve in a fifth to half a second for most direct-current machines. During this fraction of a second the voltage across the lamps is less than normal, as attested by the flicker.

If, after the current has risen to its full value of 200 amperes, another ohm of resistance is paralleled with the

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first two, the resultant resistance of the circuit is reduced to one-third ohm instead of one-half as before. The instantaneous difference between generated and load voltage is 100 — (1/3 × 200) = 33.3 volts. The dip is accordingly less than in the former case. Again, if one ohm resistance is connected in parallel with the resistances of one ohm each, the resultant resistance becomes three-fourths of the preceeding value; that is, the voltage dip is still less.

According to this reasoning, for a given added load the heavier the machine is loaded the less will be the dip. In other words, the voltage dip is dependent upon the percentage by which the load of the generator is varied. If the same percentage of load is added each time, the dips, or voltage fluctuations are practically the same regardless of the load the machine is already carrying. That is to say, if a load of 100 amperes is doubled the connected lamps flicker exactly as much as when a 300 ampere load is doubled.

Since the self-induction of a generator determines how rapidly current can be built up in it, different generators have different intervals of voltage dip. The magnitude of the fluctuation, however, is determined solely by the load; differences in machines have no effect, as shown graphically in Fig. 1. A compensated generator has a distributed winding in the pole faces so proportioned as to correctly neutralize armature reaction. Armature reaction of a generator con-

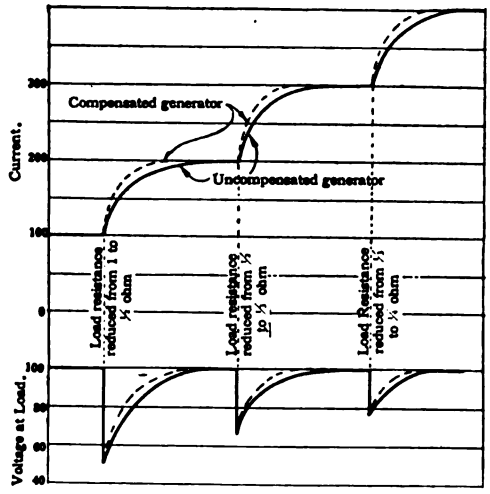
Compensated generator
Uncompensated generator
Current.
Voltage at Load.
Load resistance reduced from 1 to ½ ohm
Load resistance reduced from ½ to ¼ ohm
Load Resistance reduced from ¼ to ⅛ ohm

FIG. 1—EFFECT OF SUDDEN CHANGE IN LOAD ON DIRECT-CURRENT LOAD VOLTAGE

stitutes the major part of its inductance; therefore the self-induction of a compensated generator is relatively low. The current through a compensated machine then builds up more rapidly as loads are suddenly applied than it does in non-compensated machines. This being true, the compensated machine would have as large instantaneous drop in voltage as the non-compensated machine but should recover its normal voltage in a much shorter time.

Unfortunately, the compensated generator does not escape so easily. Although light flicker is roughly proportional to the percentage drop in voltage, it is not particularly influenced by the time required for the voltage to recover its normal value. Tests have shown that a high-speed compensated machine may, in some cases, recover voltage in one-fifth of the time required by a slow speed non-compensated machine; but the severity of the winking will not be materially more noticeable in one case than in the other, when the percentage voltage dip is the same.

As this phenomena of momentary voltage fluctuation is the result of the inductance of the system it is present on alternating-current systems as well as direct-current systems. The alternating-current systems are usually so much larger than direct-current systems that the load changes are of much lower percentage of system load and the voltage change, as explained, is correspondingly less, and scarcely noticeable.

# Factors which Influence the Performance of a Steam Surface Condenser

U. A. TADDIKEN

THE performance of a surface condenser unit is dependent upon the operation of the auxiliaries as well as that of the condenser itself The condenser in Fig. 1, built on the radial-flow principle with its characteristic steam belt which distributes the steam over the entire outer periphery of the tube nest, will condense the steam with a condensate temperature practically equivalent to the steam surrounding the tube nest. This unique principle can easily be understood from the fact that the drop of pressure from the outer to the inner part of the tube nest is small and that the condensate must pass through the steam belt and zone of higher absolute pressure before entering the hotwell, where the pressure is the same as that in the exhaust space.

If the condenser is of the straight down-flow type, the steam passes from top to bottom between the tubes into a zone of lower absolute pressure. The condensate, percolating

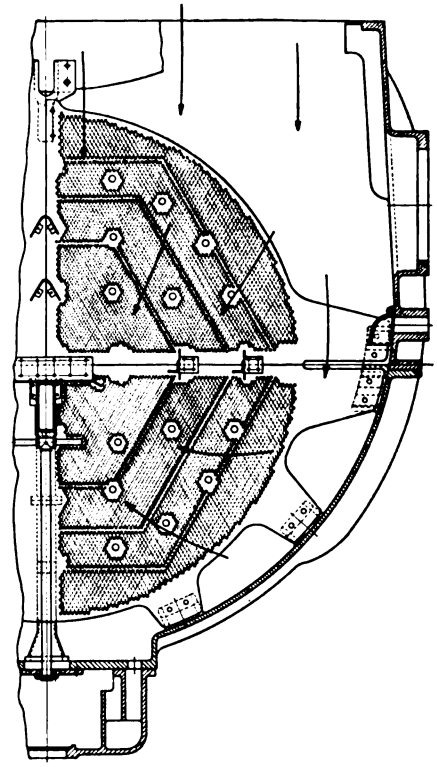

FIG. 1—SECTION OF A RADIAL-FLOW CONDENSER

through the tube nest and zone of lower pressure, decreases in temperature, due to conduction and re-evaporation or flashing.

The resistance or pressure loss through a condenser is dependent not only upon design, but upon the amount of steam flowing, the air leakage and the vacuum. By referring to Fig. 2, the specific volume of steam for different pressures can readily be determined, and it will be noted that for a change from 28 to 29 inches of vacuum, the volume is practically doubled. If a change of condition from that anticipated in the design takes place, a change in the pressure drop can be expected. With increased pressure drop, a depression of condensate temperature must be expected in a down-flow condenser.

The performance of a condenser is normally expressed in terms of heat transfer. That is, the number of B.t.u. per square foot of condenser tube surface per hour per degree of mean temperature difference has become the standard basis of comparison. The rate of heat transfer in condensers is dependent upon many factors, such as water velocity in the

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tubes, the scavenging effect of the steam through the spaces between the tubes, the air removal, and the internal and external condition of the tube surfaces

The heat transfer, with clean tubes, varies approximately as the square root of the water velocity. For general calculations and practical purposes, the above value can be used with safety. Hence it is desirable, when designing a condensing unit, to consider a reasonably high water velocity. This will enable a smaller unit to accomplish the work intended.

The higher water velocities have another and indirect influence upon the heat transfer. They maintain cleaner

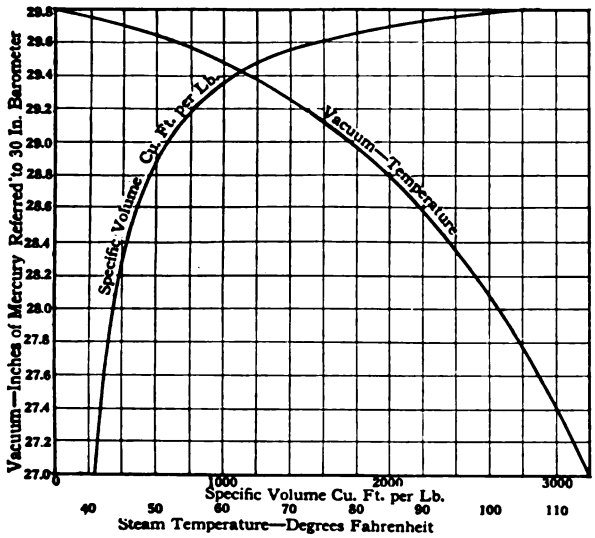
Vacuum—Inches of Mercury Referred to 30 In. Barometer
Specific Volume Cu. Ft. per Lb.
Vacuum—Temperature
Specific Volume Cu. Ft. per Lb.
Steam Temperature—Degrees Fahrenheit

FIG. 2—STEAM VACUUM-TEMPERATURE-VOLUMN CURVES

tubes, due to the greater turbulence and scouring effect, thereby preventing precipitation of fouling matter. It is often possible to maintain higher velocities without marked increase of power by selecting the circulating pump with the proper efficiency characteristic for normal operating condition.

The water film with its numerous bubbles of air and non-condensable vapors surrounding the tube during condensation affects the heat transfer. Therefore, the tubes should be arranged so that the passing of steam through the tube nest will not be restricted and at the same time will have sufficient velocity to scavenge the condensing surface and keep the water film reduced to a minimum. The determination of the best tube spacing for all vacuum and load conditions is quite a problem. Ordinarily an arrangement is adopted which is most satisfactory for normal operating condition.

The highest rate of heat transfer can be obtained only with the complete removal of air and non-condensable vapors from the condenser shell. Air removal is imperative, for air collected in the condenser near the point of air offtake forms a blanket which prevents condensable vapors from entering the affected section. The blanketed section becomes inactive and, therefore, causes a reduction of overall heat transfer of the unit. This feature was early realized by condenser builders and was accomplished by the more efficient air pumps. Later developments have proved the steam-jet air ejector to be a very effective and reliable air extractor.

One of the most important conditions affecting the heat transfer, and one which so often seems to be disregarded, is that of tube cleanliness. It is an economic necessity to maintain both the interior and exterior surface of the tube in a condition of cleanliness as near to that of a new tube as operating conditions will permit.

The curves of Fig. 3 show the results of a test conducted on a single tube specially arranged in a large condenser. The effects of tube cleanliness were established for various velocities in the single tube, while the remainder of the condenser operated under the normal conditions. The results are so surprising that one cannot but realize the advantage of clean tubes. Taking six feet per second water velocity as a base, it will be noted that the heat transfer obtained is 190 B.t.u. for the fouled tube, 437 B.t.u. for the same tube after a thorough internal cleaning with wire brushes, and 520 B.t.u. for a new tube, a percentage increase of 230 and 274 percent, respectively. Such a relative comparison could be established on units in operation, at little cost for labor and material. With such information, the operator would have some idea of what could be expected by cleaning the tubes.

Excessive free air leakage into the condensing system is a condition that often affects the performance and seems to be considered least. The methods used in searching for leaks are often so crude that the time spent could be considered an absolute waste. For instance, the candle-flame method should be associated with the days of the reciprocating engine and 25 inches of vacuum and not with the present-day turbine and 29 inches of vacuum. Practice has dictated that a water or air test be conducted with the greatest of care to make the condensing system tight.

In very large units where it is impractical to subject the shell and foundations to the weight or pressure of the water, a compressed air test is used. The condenser and turbine or the vacuum system is subjected to an air pressure of approximately 5 to 10 pounds gage, while the whole exterior surface is being painted with a concentrated soap solution. When applying the soap solution, close observation should be made for leaks in the form of bubbles or escaping air jets. This method, carried out properly, has given very satisfactory results.

In making tests for air leaks, it is necessary not only to see that the condenser shell is tight, but also that all parts of the entire system that may be under vacuum are tight. Air leaks are quite common in poorly packed valve stems that may withstand water tests due to swelling of the packing at the time of tests. Leaks are also common in the turbine casing, glands, drains, equilibrium pipes, etc. Many modern

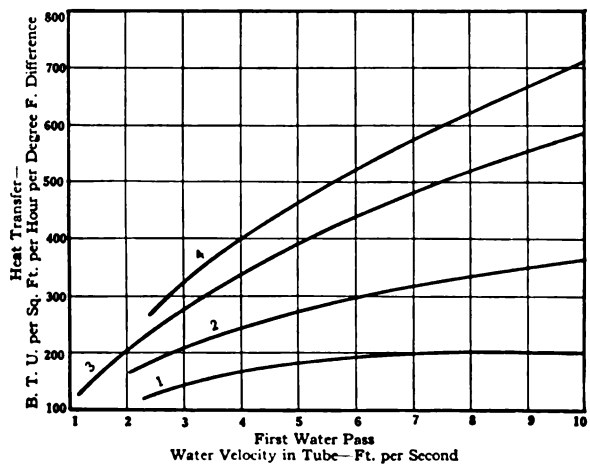


FIG. 3—EFFECT OF TUBE CONDITION ON HEAT TRANSFER

1—Heat transfer with original tube in fouled condition five days after cleaning with rubber plugs.

2—Heat transfer rate with original tube in fouled condition five days after cleaning with rubber plugs.

3—Heat transfer rate with original tube immediately following cleaning with wire brushes.

4—Heat transfer rate with a new tube substituted for original tube.

plants have provided air-measuring devices to enable the operators to determine the air leakage and assist their organization in keeping leakage below a set standard.

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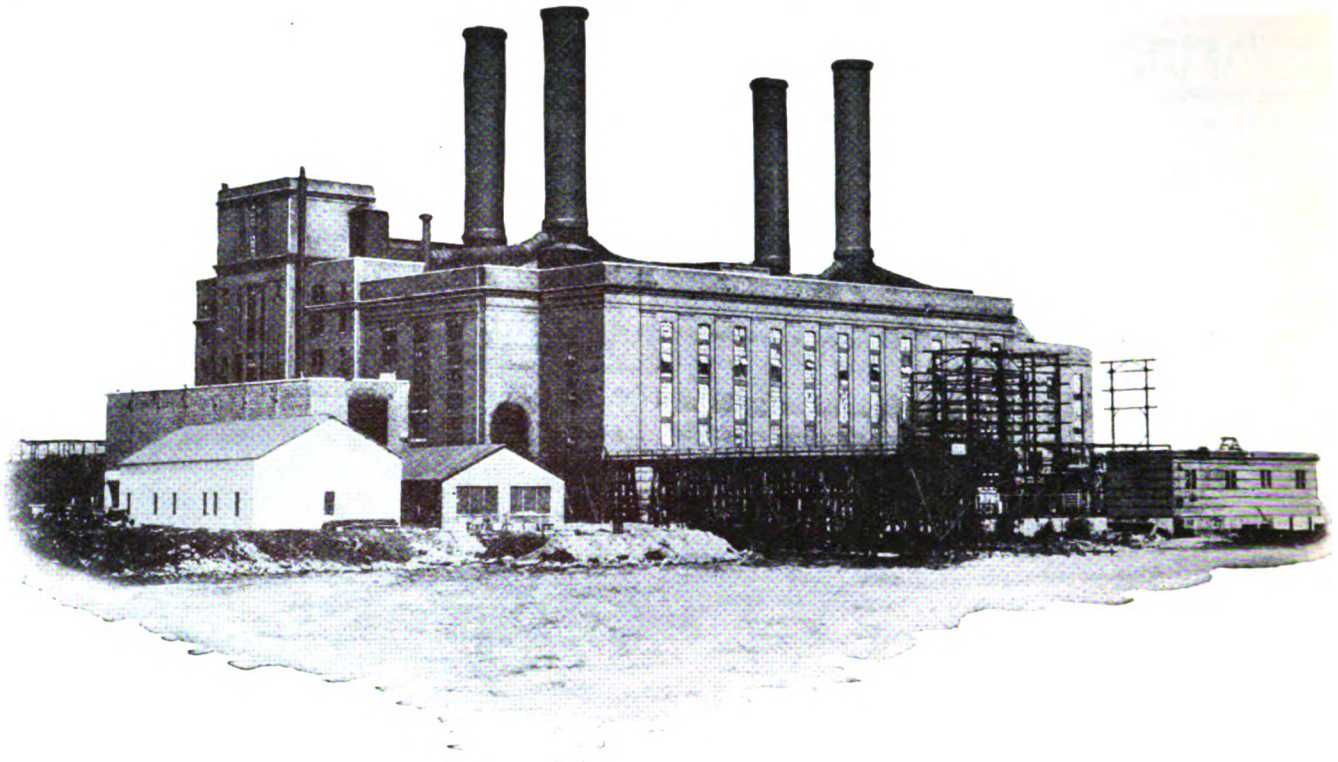

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# Stroboscopic-Neon Lamp Method for Measuring the Slip of Induction Motors

CARL C. NELSON

THE slip of an induction motor, expressed in revolutions per minute, is the difference between the speed of the rotating field and that of the rotor. The speed of the rotating field is usually spoken of as the synchronous speed. For practical purposes it is more convenient to express the slip as a fraction of the synchronous speed, in which case the slip is defined as the ratio of the difference between the synchronous and rotor speeds to the synchronous speed. Thus if the synchronous speed is 1800 and the rotor speed is 1740 r.p.m., the slip is,—

$$S = \frac{1800 - 1740}{1800} = 0.033 \text{ or } 3.3 \text{ percent..}$$

In the testing of induction motors it is desirable to determine the slip at different loads in order to know accurately the speed at which the motor is running under the different loads. The slip is an indication of the rotor copper loss.

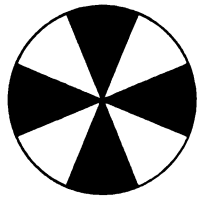

FIG. 1—STROBOSCOPIC DISC FOR A FOUR-POLE MOTOR

When it is expressed in percent and subtracted from 100, the value obtained gives the rotor efficiency. A change in speed therefore represents a change in the efficiency of the motor.

Various methods of measuring slip have been used. Some of these have been rather intricate and expensive, and to some extent inaccurate. As a result of these objections, the stroboscopic method using a neon lamp has recently come into use because of its simplicity and convenience.

The stroboscopic method consists in the observation of successive positions of a rotating disk by means of a beam of light periodically interrupted. The disk has its surface divided into a number of regularly spaced black and white sectors, preferably the same number as the motor has poles. A disk for a four pole motor is shown in Fig. 1.

When the disk is fastened to the shaft of the motor and rotated, the colors merge and tend to produce one color.

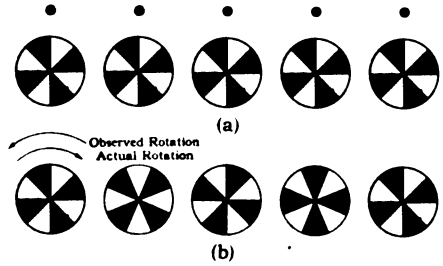


FIG. 2—SUCCESSIVE APPEARANCE OF STROBOSCOPIC DISC

When (a) motor is running at synchronous speed and when (b) motor is running at less than synchronous speed.

However, the separate colors can be distinguished by illuminating the disk with a light which is periodically interrupted in synchronism with the frequency of the supply circuit to which the motor is connected. Assuming for the present that the light is interrupted at the correct frequency, then, if the rotor is rotating at synchronous speed, the disk appears to be standing still, for a position occupied by a black sector at one instant of illumination is exactly occupied by the next black sector at the next instant of illumination. This action is rapidly repeated, thereby producing the standstill effect. However, the induction motor usually runs at some speed below synchronism so that the black sectors appear to rotate. At one point of illumination a black sector has a certain position, while at the next point of illumination the next black sector has a position slightly back of that occupied by the first sector. This action continues for each point of illumination, causing the disk to appear as though it were rotating slowly backward. The conditions mentioned above are shown in Fig. 2. For convenience, the dots represent the points of illumination.

The number of revolutions the disk appears to rotate per minute represents the number of revolutions per minute below synchronism at which the motor is running; or in other words, represents the slip in revolutions per minute. This value multiplied by 100 and divided by the synchronous speed gives the slip in percent.

Recently, the neon gas lamp has been adapted to the stroboscopic method of measuring slip. This type of lamp is also known as a gaseous-conduction or gas-discharge lamp. In simple form it consists of a sealed glass tube containing a gas and two plates as shown diagrammatically in Fig. 3.

If an increasing potential is applied to this lamp no current flows until a certain critical voltage is reached, at which time a disruptive discharge takes place. This is known as a glow discharge, as it is accompanied by the development of light. The flow of current continues until a definite lower value of voltage is reached, at which time the current stops. The exact values of the starting and stopping voltages depend

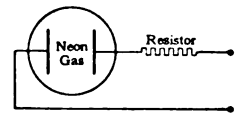


FIG. 3

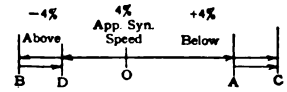


FIG. 4

FIG. 3—CONNECTIONS FOR NEON LAMP
FIG. 4—REPRESENTATION OF SLIP VECTORS

upon the characteristics of the lamp. Thus if an alternating-current potential is applied to the lamp, the periodically varying voltage produces periodic discharges or flashes of light. This is exactly what is desired for stroboscopic work.

The frequency of the light flashes is next to be considered. If there were no slip in an induction motor, the rotor would advance one pole during each one-half cycle of the applied voltage. During this time interval each black sector would advance to the position just occupied by the preceding one. It is thus shown that the disk must be illuminated twice every cycle. This is accomplished by connecting the neon lamp to a circuit whose frequency is the same as that to which the motor is connected.

An alternating-current arc lamp can be used in the same way, but is cumbersome and requires much more attention than the neon lamp. Furthermore, the color of the glow from the neon lamp is of striking contrast to sunlight, which greatly facilitates stroboscopic observations.

A complete set of apparatus built for use with the neon lamp method consists of a stand, lamp bracket, gear box, universal coupling and coupling socket. The lamp bracket and gear box should be mounted on a stand so as to be adjustable to the desired height.

The neon lamp is mounted in a socket, and used on a 220 volt circuit. It is inclosed and protected by a box, the front of which has a slot to allow the light to shine upon the disk. At the time of discharge the potential drop across the plate terminals is reduced. It is therefore necessary to provide a stabilizing resistor of 3000 ohms in series with the lamp to limit the current.

When the slip is unusually high a gear box is used. This consists of a set of three meshed gears, the ratio of the

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common one to the other two being 0.96 and 0.92 respectively. The disk is fastened to the common gear and driven through one of the other gears, which in turn is driven by the coupling to the shaft of the motor. The coupling fits into a socket fastened to the end of the shaft. If the 0.96 gear ratio is used the disk will revolve faster than the motor and at exactly four percent slip the disk will appear to be standing still. In using the gear box, the slip of the motor in percent of the synchronous speed is expresed by,—

$$S = 100\left[(1 - R) \pm A\ (R/N)\right]$$

where $R$ = gear ratio (less than one),
$A$ = apparent speed of disk in r.p.m.,
$N$ = synchronous speed of motor in r.p.m.

The sign of $A$ is determined by slightly increasing the load on the motor. If the apparent speed of the disk increases, the sign is plus, and if the apparent speed decreases, the sign is minus. This is explained as follows: Assuming that the 0.96 gear ratio is being used, an apparent synchronous speed is obtained at exactly four percent slip. If the motor is running below the appart synchronous speed, the slip can be represented by a vector $OA$, Fig. 4. Similarly, when the motor is running above the apparent synchronous speed, the slip can be represented by the vector $OB$. At a certain value of slip it is not known whether the value is above or below the apparent synchronous speed point $O$. If the load is increased and the apparent speed of the disk increases, it is recognized that the motor was running below the apparent synchronous speed and the slip is four percent $+ OA$. The increase in apparent speed in terms of slip, is represented by $AC$, Fig. 4. If the apparent speed of the disk decreases when the load is increased, the motor was running above the apparent synchronous speed and the slip is four percent $- OB$. In this case the decrease in apparent speed of the disk, in terms of slip, is represented by $BD$, Fig. 4. It must be kept in mind that the actual slip of the motor increases when the load is increased.

In any method of measuring slip, such as the one outlined herein, the accuracy of the result is dependent upon the ability of the tester to count the apparent revolutions of the disk satisfactorily. With a fairly competent tester results indicate that this factor becomes negligible when compared with the results of a number of other methods used. As mentioned previously, the ease of handling and the absence of complicated apparatus have also contributed in making this method a decided improvement over other commercial methods.

# The JOURNAL QUESTION BOX

Our subscribers are invited to use this department as a means of securing authentic information on electrical and mechanical subjects. Questions concerning general engineering theory or practice and questions regarding apparatus or materials desired for particular needs will be answered. Specific data regarding design or redesign of individual pieces of apparatus cannot be supplied through this department.

To receive prompt attention a self-addressed, stamped envelop should accompany each query. All data necessary for a complete understanding of the problem should be furnished. A personal reply is mailed to each questioner as soon as the necessary information is available; however, as each question is answered by an expert and checked by at least two others, a reasonable length of time should be allowed before expecting a reply.

2805—METERING THREE-PHASE POWER WITH ONE METER—A single-phase meter having the current transformer connected in the primary line and the potential transformer in the secondary of the transformer which is used to supply a six-phase rotary converter is shown in Fig. (a). The power transformers are connected

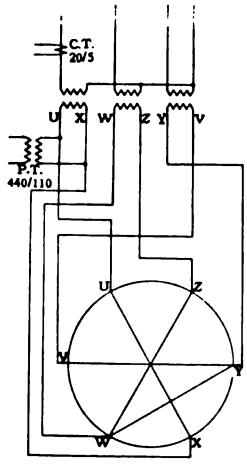


FIG. 2805 (a)

star on the primary side for 60 000 volts while the secondary of the transformer is six-phase, 430 volts. The direct-current side of the rotary is for 600 volts. There was 236.2 kv-a in the circuit using a voltmeter and ammeter and the disc of the meter did not turn. The method used is to take the power used in one phase and multiply by three for the total power in the three phases. Will you please advise if the condition is such that the meter is connected in the phase with the low power-factor and if any method can be used to correct this condition with the present equipment. L. C. H. (NEW YORK)

1—When the meter is connected as you have shown in Fig. (a), it should measure one-third of the total power supplied in the converter. This measurement does not depend upon the power-factor of the circuit. 2—In a circuit such as the one shown, each of the three phases has approximately the same load and also each phase has the same power-factor. This is the reason that it is possible to meter the circuit with one single-phase meter and multiply the reading by three. The method is sufficiently accurate for most commercial measurements. 3—We would suggest that you first inspect the meter to determine whether or not the trouble is in the meter itself. If the meter is all right then it is probable that the potential transformer is connected across the wrong voltage. 4—We recommend that you check your connections again. If instead of the potential being connected across lines $U$ and $X$, it is connected across $W$ and $Y$, at unity power-factor, the meter will not rotate as voltage $WY$ is 90 degrees displaced from $UX$. C. O.

2806—INDUCTION MOTOR PUNCHING AREA—When measuring the core area of certain motors which have stator stampings like Fig. (a) should you measure the core at $A$ or $B$ or take

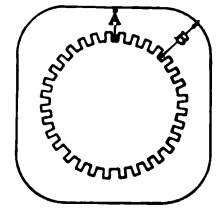


FIG. 2806 (a)

an average of the two in order to design a new winding after Mr. Dudley's formula as published in his book. G. W. S. (CALIF.)

Use $(A + B) \div 2$ for all ordinary cases. A. M. D.

2807—LENGTH OF EQUALIZER—Is the equalizer connection of the two similar rotary converters shown in Fig. (a) too long to give satisfactory parallel operation? D. W. (CALIF.)

The resistance of the equalizer required to give satisfactory division of current between two compound synchronous converters in general is not a definite value. The lower the resistance of this lead the better will be the load division for a given application. Its length is obviously of no consequence except as it affects the total resistance. For the ordinary synchronous converter installations, where the length of the equalizer run does not exceed twenty five to thirty feet, it

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is common practice to use an equalizer of one half the size of the main leads. For greater equalizer lengths it is necessary to increase the size to obtain the same degree of load division. The information supplied does not give the bus voltage or the resistance of the series fields. For 600 volt railway converters 0.000 75 ohms will be assumed for the parallel resistance of the series fields and grid shunts, however, this

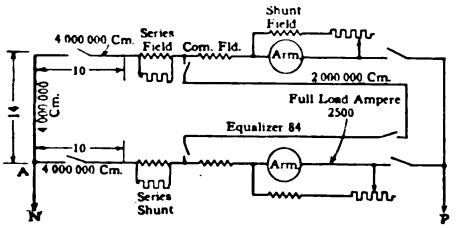


FIG. 2807 (a)

value is quite variable depending upon the particular machine design. For 250 volt industrial machines this resistance is assumed to be 0.000 19 ohms. The 24 feet of negative bus would have a resistance of 0.000 0647 ohms, which, being in series with the series field of the No. 1 machine would give a total resistance to the point *A* on the negative bus of 0.000 0647 + 0.000 75 = 0.000 8147 ohms. For the industrial converter this resistance would total 0.000 2547 ohms. The resistance of the equalizer is 0.000 4525 ohms approximately. For synchronous converters operating in parallel the resistance of the equalizer should equal or be less than the series field and bus resistance. Hence, in this case the equalizer for the assumed railway machines is of ample size while for the industrial machines it should be increased in size by an additional 2 000 000 circ. mil cable. Synchronous compound-wound converters, due to their more pronounced drooping voltage characteristic, as compared with the more flat characteristic, of the compound-wound generator, do not require as low an equalizer resistance to obtain the same degree of load division. C. A. B. & H. A. R.

2808—SYNCHROSCOPE CONNECTIONS—Assume that the potential transformers have like characteristics and standard connection to a synchronoscope on the two three-phase four-wire lines of Fig. (a). If one primary of transformer on line 2 is changed from phase *b* to *c* as shown at *X*, what effect will this have on the synchronoscope when synchroniz-

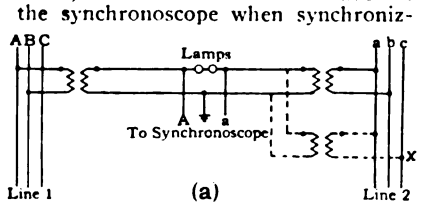


FIG. 2808 (a)

ing the two lines? When lines are in synchronism will the synchronoscope show zero degrees or will it be displaced due to this connection? If displaced would it be permissible to move the indicator to the zero position when lines are in synchronism? While this complicates wiring and is not the best practice, will the result be the same as if the standard connection is used? A. B. G. (CALIF.)

If two machines are running at the same speed, but one lags behind the other, i.e., the maximum value of one voltage wave occurs a fraction of a cycle after that of the other, then the pointer will assume a definite position. If the maximum of the incoming wave occurs 1/4 cycle (90 degrees) after the maximum of the bus-bar wave, then the pointer will indicate 90 degrees from the synchronous point. If it occurs 120 degrees later, the pointer stands 120 degrees away, etc. In the case in question, if the phase rotation is *a-b-c-*, and the synchronoscope leads on the incoming machine are changed from *ab* to *bc*, then the point of synchronism will be 120 degrees ahead of the zero point on the synchronoscope scale. Should an attemept be made to synchronize at indicated synchronism the results would be disastrous. Of course if the indicator were displaced through the 120 degrees true synchronism would be again shown. This procedure is not recommended as the instruments are made up according to standard plans and such changes may be directly responsible for some serious difficulty. If it is necessary to change from phase *ab* to *bc* on one machine, the same change should be made on the bus connections, thus making any change in the synchronoscope itself unnecessary. H. W. P.

2809—REVERSING THE DIRECTION OF A DIRECT-CURRENT GENERATOR—We have a 35 kw compound commutating direct-current generator, 125 volt, 850 r.p.m., belt driven. The generator does its work splendidly. We want to reverse rotation of the generator. What steps should I take to make this machine build up its voltage when rotation is reversed. R. T. P. (KENTUCKY)

In order to reverse rotation on a compound direct-current generator but keep the polarity of the line the same and permit the generator to build up voltage of the original polarity, the fol-

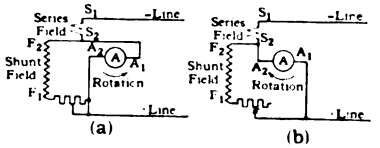


FIG. 2809

lowing operations should be followed: Connect plus armature lead, and minus shunt field lead to plus series field lead. Connect minus armature lead to plus line. Other connections to be as before. See sketch. If the generator were a non-commutating pole machine, the brushes would have to be shifted forward in the new direction of rotation for good commutation. H. C. M.

2810—DISTRIBUTION SCHEME—I would appreciate knowing what results may be expected employing a system of distribution as shown on Fig. (a). I believe some central stations are operating a system like the one shown but are experiencing difficulties due to interference with the telephone company and radio broadcast listeners, and are also having trouble maintaining good regulation on their lighting circuits. Any information on this subject will be appreciated. P. J. K. (NEW JERSEY)

There would inherently be a certain amount of voltage unbalance in a system of the type shown in Fig (a), since all of the single-phase load must be taken off of one phase of the transformer. The amount of unbalance will depend on the size of the single-phase load as compared to the three-phase load. Whether or not the unbalance in the transformer and secondary system will be still further increased in the primary feeders depends on how the single-phase loads are balanced. If the single-phase load is taken from a different phase on each of three adjacent transformer banks, it is probable that the load on the primary will come rather close to being balanced. This arrangement is possible as long as the secondary systems fed by the different transformer banks are entirely independent for, under this condition, a different phase on each transformer may be grounded. With the system shown, it will be necessary to use a transformer of higher rating for that leg of the transformer bank which carries the single-phase load. The only thing that can be said regarding tele-

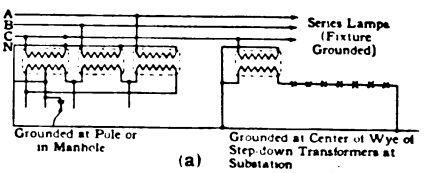


FIG. 2810

phone interference is that there is a possibility of such difficulty due to the unbalanced conditions. In the secondary system the current and voltage will undoubtedly be unbalanced but no interference trouble should be experienced since this is only a 230 volt circuit. On the high voltage side the unbalanced conditions in the line will give unbalanced electric induction and whether or not this will cause interference in neighboring telephone lines will depend on the amount of unbalance, the distance between the power lines and telephone lines and the general arrangement of the former. As an example of the last point, some companies follow the practice of taking one of the three-phase wires around a block separate from the other two wires for street lighting and other such purposes. Such a condition is liable to lead to telephone interference. There appears to be no cause for radio interference in the system itself. If the street lamps shown are series arc lights, trouble will very probably be experienced but this is due to the lamps themselves and will hold true on any type of system. T. J. B.

2811—HOT SPOT INDICATORS—I—The maximum allowable temperature by the hot spot temperature indicators on a bank of O.I.W.C. power transformers is 95 degrees C. Under actual maximum load conditions the hot spot temperature is 80 degrees C. Assuming that the hot spot indicators were removed, it would then be necessary to depend upon the oil thermometers for temperatures. What is the maximum allowable temperature for such transformers, as indicated by the oil thermometers only? If the maximum oil temperature must be limited to, say 80 degrees C., what harm would result from operating the transformers at this temperature instead of at 95 degrees C. as shown on the hot spot indicator? As you know, many large O.I.W.C. transformers have never

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been equipped with hot spot indicators, therefore, temperatures must be obtained from the oil thermometers, the limit in this case being about 80 degrees C. R. B. G. (CALIF.)

The maximum allowable hot spot temperature of a water-cooled transformer is 90 degrees C., according to the standards of the A. I. E. E. The usual operating oil temperature for a water-cooled transformer having a full-load temperature rise of 55 degrees C. is about 65 or 70 degrees C. when the temperature of the cooling water is 25 degrees C. The temperature of the hot oil in a transformer is not a safe guide to use in loading a transformer. The temperature of the copper is always higher than the temperature of the oil when the transformer is carrying load. The difference between the temperature of the copper and of the hot oil is a variable depending upon the current flowing in the windings, and it increases roughly as the square of the current. In order to keep within the recognized limits of temperature for the copper, the permissible oil temperature would, therefore, have to be reduced for a low temperature of cooling medium in order to offset the higher temperature gradient of the winding if the transformer is to be loaded above its nameplate rating. It is obvious then that when the temperature of the cooling water is low and the transformer is loaded above its nameplate rating, the oil temperature may be within a limit of 65 or 70 degrees and yet the temperature of the windings may exceed a dangerous temperature. A good rule to follow in loading a water-cooled transformer above its nameplate rating because of a low water temperature is to allow one percent additional kv-a output above the nameplate rating for each difference between the standard temperature of 25 degrees C. for the cooling water and the actual lower temperature of the cooling water. A limit of 125% should be observed in following this empirical rule. W. M. B.

2812—REDUCTION OF INTERFERENCE FROM THIRD HARMONIC IN AN UNGROUNDED STAR-STAR SYSTEM—Fig. (a) illustrates a connection used to step down from a 110 kv delta ungrounded 60 cycle system to a 44 kv star ungrounded neutral system. In order to reduce interference with neighboring communication services a bank of three 100 kv-a units have been connected as shown. There is available a bank of three 1250 kv-a, 63 500/13 200 volt transformers and it is suggested that further improvement might be had by connecting these as in Fig. (c). These 1250 kv-a units have already been connected at reduced voltage as in Fig. (b), without much improvement resulting. The impedance, resistance and reactance of the 5000 kv-a units is 11.1 percent, 0.825 percent and 1.78 percent. The 1250 kv-a have impedance, resistance and reactance of 11.2 percent, 0.77 percent and 11.18 percent. The 100 kv-a units have an impedance, resistance and reactance of 1.96 percent, 0.825 percent and 1.78 percent. The exciting currents for the 5000 kv-a, 1250 kv-a and 100 kv-a units are respectively 2.95 percent, 3.6 percent and 4.48 percent. Please state:—1—Whether the connections in Fig. (c) should be superior to the connections in Figs. (a) and (b) for eliminating third harmonic voltages from the 44 kv lines. 2—Considering the effect of the 1250 kv-a units only, will they be most effective at normal voltage or at the reduced voltage, and why? 3—Rushmore & Lof in "Hydro-Electric Power Stations" p. 406-7, state that "third harmonic voltages (in star-star transformers) are practically eliminated—when the neutral of either side is connected to the neutral of a star-delta bank across the lines on the same side (primary or secondary)". My opinion is that the 100 kv-a units would be completely effective except for their small capacity and that the reason for the indifferent success of the 1250 units connected as in Fig. (b) is accounted for by the use at reduced voltage. If the latter are connected as in Fig. (c)

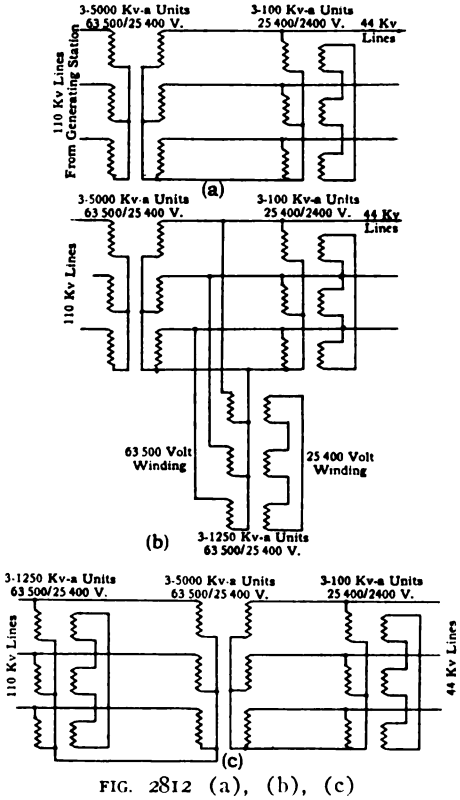


FIG. 2812 (a), (b), (c)

they should eliminate third harmonic voltages. Am I correct? J. M. H. (CANADA)

1—If the third harmonic voltage on the 44 kv line is being caused by the 500 kv-a units, the connection of Fig. (c) would likely take care of the trouble, as it is superior to the ones of Fig. (a) and (b). There seems to be an error in your connections of Fig. (b). The one shown is not at all effective for eliminating the third harmonic voltage. 2—The 1250 kv-a units would be more effective on the 110 kv side of the 5000 kv-a units, for the reason that larger third harmonic magnetizing current is required on the low voltage side than on the high side and further by reason of a lower flux density, in the 1250 kv-a units if connected on the low side, and therefore the third harmonic voltage across the transformer would be greater which would mean a larger 180 cycle voltage on the 44 kv line. 3—Your opinion that the 100 kv-a transformers with the star-delta connection would be sufficiently effective (not completely) for eliminating the 180 cycle voltage being caused by the 5000 kv-a units except for their small capacity is correct. Should the 1250 kv-a units be connected star-delta on the 44 kv side of the 5000 kv-a units they would not be very effective for reducing the third harmonic voltage because the 180 cycle magnetizing current flowing would result in a very large 180 cycle voltage on the 44 kv line. The connection shown in Fig. (c) should reduce the 180 cycle voltage to about one percent, provided the trouble is being caused by the 5000 kv-a units. In the case the trouble is partially due to other star-star connected transformers on the 44 kv line, it would be preferable to connect the 1250 kv-a units star-delta (interconnected neutrals) on the 110 kv side of the 5000 kv-a units and connect the 100 kv-a units star-delta on the 44 kv line near to the troublesome bank. J. W. B.

2813—CHANGING MOTOR VOLTAGE—I have a synchronous motor that I would like to change from 2300 to 440 volts. It is rated at 125 hp, 60 cycles, 8 poles, 31 amperes, 2300 volts, has 7 turns of two No. 10 double cotton covered round wires in parallel, 96 slots, span 1-13, connection is series star, bore inside 25 inches; outside diameter 33 inches, length of iron 8½ inches with three spacers 10 inches, each spacer is ½ inch, slot depth 2⅛ inches. Will this winding work in this frame? 6 turns of two No. 8 double cotton covered round wire; span 1-13; connection 4 circuit star. If this will not work, please let me know why, and what will? H. J. P. (N. Y.)

It is impossible from the data given to check how the new winding will fit in the slots. Assuming it is satisfactory from this standpoint, changing the winding from series star to four parallel star should make it suitable for 560 volts. A further change from seven series turns per coil to six series turns per coil would make it suitable for 480 volts. Changing the chording from full pitch to 1-10 will make it suitable for 443 volts, which is as near as you can get to the original performance of the motor. With a winding as suggested the motor performance should be practically the same as before the change with somewhat less copper loss due to the chording. C. R. R.

## CORRECTION

The expression "$\alpha - 180°$" in Fig. 1 of the article by D. F. Alexander in the JOURNAL for February 1928, p. 77 should be read $\alpha = 180° - \beta$. The formula for chord factor in Fig. 2 should be

$$\text{Chord factor} = \sin 1/2\left(\frac{\text{Percent Pitch}}{100}\right) \times 180°.$$

The expression in Fig. 3 "Full Pitch 7 Slots Throw" should read 77.8 percent 7 slots Throw.

In the article by P. H. Robinson in the JOURNAL for February 1928, p. 65

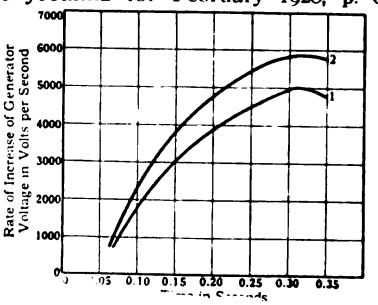


Fig. 11 is incorrect. The figure here shown should be substituted.

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# THE ELECTRIC JOURNAL

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**Changes in Design Practice**

We are all familiar with the changes that are going on in the personal habits of most people. Money which was formerly spent on the home is now used for buying automobiles. Changes in wearing apparel have almost eliminated the demand for some things and created a demand for others.

Changes in the design of electrical apparatus have been almost as radical as those mentioned above. At one time free use was made of cast iron. The apparatus was heavy and rugged and new types required only drawings and patterns. If many similar parts were made, some machining fixtures were used, but in general, machining was largely laid out by hand. The total development expense was not large and changes in the design could be made readily and cheaply, but the cost of the apparatus was high.

Sheet steel has now largely superseded cast iron. Insulated parts are made up of moulded material. The production of individual pieces has greatly increased and so has the development expense. Punched and fabricated steel requires expensive tools and fixtures; and in order to justify this expense by increased production, it is necessary to provide manufacturing fixtures for the other operations, so that little or no layout work is necessary and usually little fitting. This change has made present-day apparatus smaller, lighter and less expensive, but has increased the investment required for its manufacture.

Large frames, bases, cabinets, etc., are made from sheet metal and standard structural shapes. The parts are welded together and in some cases the sheet metal is cut to the desired shape by means of the electric arc. These structures are light, rigid and free from breakage. No heavy castings are required but, when made in quantity, they require fixtures for their economical production.

The passing from cast iron to fabricated material has resulted in other important changes in the industry. One of the most notable is the decrease in the demand for castings. Foundries find that their capacity is in excess of the demand and already are making plans for utilizing their equipment in some other way.

The very great increase in the cost of shop equipment has placed a heavy burden on the design and manufacturing engineers. New designs intended for quantity production must be more thoroughly analyzed and tested before the expensive tool equipment is designed and built. The commercial department has an added responsibility in forecasting demand, as the expense and type of tools depends on the quantity produced.

At the present time the design of electrical apparatus is definitely towards fabricated steel parts, punchings, moulded insulation and, as far as practical, nonbreakable material. The designs tend towards compactness and neatness. Pleasing appearance of the apparatus is becoming more important. H. D. JAMES

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**Oil Governors for Turbines**

In the development of steam turbines, improved reliability is the first consideration. In the past, dependability in turbine operation has been largely a function of the adequacy of turbine blades, as their failure has been the source of the highest maintenance expense confronting the operator. The development of superior metals for turbine blading, together with a more intimate knowledge of the stresses to which blades are subjected has advanced the art of building reliable turbines.

A trend of general improvement has been in evidence throughout turbine design; so much so, that the modern, large, central-station prime-mover is now conspicuous for its high standard of reliability. However, in spite of years of investigation of constructions aimed to reduce maintenance charges to a minimum, there are still possibilities for advancement. For example, the older flyball governor, adopted by turbine builders in the early days of the art, has been highly perfected. Employed in the construction of this governor there are, however, essential devices, such as pins, gearing and knife edges, which are susceptible to wear, and consequently require periodical replacement. These are eliminated in the more modern oil governors.

In this issue appears the first installment of a review of recent oil governor development by Mr. H. F. Schmidt, an engineer of wide experience in turbine design and construction. It has been through Mr. Schmidt's keen foresight and unceasing endeavor, that the present highly satisfactory status of this type of governor has been reached. This review in its first part is historical and traces the development of one of the outstanding achievements in turbine practice.

Inasmuch as the introduction of the oil governor has effected a reduction in turbine outages and maintenance costs, it constitutes a new and important step toward the attainment of practical dependability. Today there are more than 240 turbines in capacities from 500 to 40 000 kw, controlled by such mechanism. Before the end of 1928, one 60 000 kw unit and one of 104 000 kw will be in operation and controlled by oil governors. It is believed, that this development will be welcomed by the turbine operator, and will win increasing favor as its advantages are better known.

A. D. HUNT

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# Fluid Governors for Prime Movers

## I--Historical

HENRY F. SCHMIDT
Consulting Engineer, South Philadelphia Works
Westinghouse Electric & Mfg. Co.

It is the intention, in the following articles, to discuss only those governors which maintain the speed of a prime mover substantially constant, and in which the fluid acts as the speed responsive means, without the use of centrifugal weights. Fluid governors may be divided into four general classes; centrifugal, gear and vane pumps, scoop and Venturi. With any of these classes of governors either liquids or gases may be used as the media. For reasons which will appear, gases such as air are generally undesirable, and, broadly speaking, oil is the most suitable medium, since this is necessary in the lubrication system even though no governor is employed.

WHILE there were earlier crude forms of fluid governors, the first real governor employing a fluid as the governing medium, of which there appears to be any record, is that employed by Parsons in about 1884 on his earliest steam turbines.

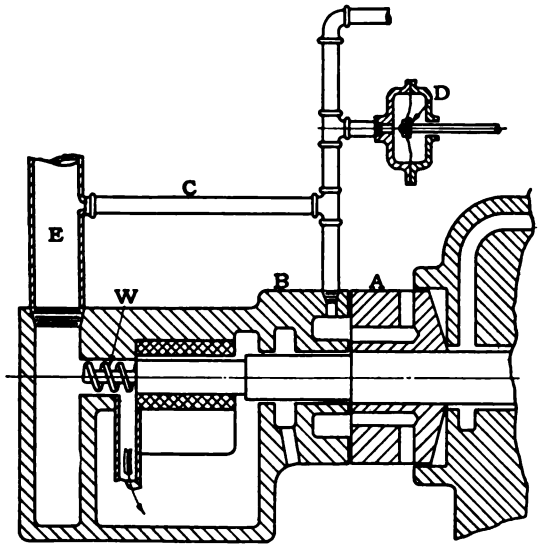


FIG. 1—THE FORWARD END OF PARSON'S FIRST TURBINE

Even these governors did not keep the speed constant, but rather maintained a constant voltage on the driven generator. A cross section is shown in Fig. 1 of the forward end of Parsons' first turbine, in which the governor mechanism consisted of a collar *A* on the shaft, which had radial and axial holes drilled in it, forming, in effect, the runner of a small centrifugal blower. On the side having the axial holes, this collar ran in close proximity to the bearing housing *B*, which contained a chamber connected by the pipe *C*, with the regulating diaphragm *D*, and also the chamber *E*, above the oil reservoir. The action of this governor, which used air as a medium, was as follows:—

The centrifugal force acting on the column of air in the radial holes in the collar reduced the pressure in the chamber *B*, the reduction of pressure behind the diaphragm *D* caused the spring to be compressed by atmospheric pressure acting on the opposite side of the diaphragm. The motion of the diaphragm, transmitted to the valve, closed the latter as the pressure at the entrance of the collar *A* was reduced by centrifugal force with increase of speed. This part of the governing mechanism by itself would tend to maintain the speed constant, neglecting variations of density of the air due to changes of temperature and barometer. However, as these turbines were used to drive direct-current generators, the characteristics of which were such that they had considerable voltage drop with increase of load, a supplemental governing mechanism was provided in the valve mechanism shown in Fig 2. This consisted of an arm, pivoted above the yoke of the generator fields in such a manner that, as the current in the field winding decreased, the decrease of flux in the field permitted the spring to pull the arm to a greater angle with the yoke. This uncovered a small port *B*, Fig. 3, which permitted air to enter behind the diaphragm *D*, Fig. 1, and thus caused the governor valve to open more until the speed increased sufficiently to bring the voltage back to normal.

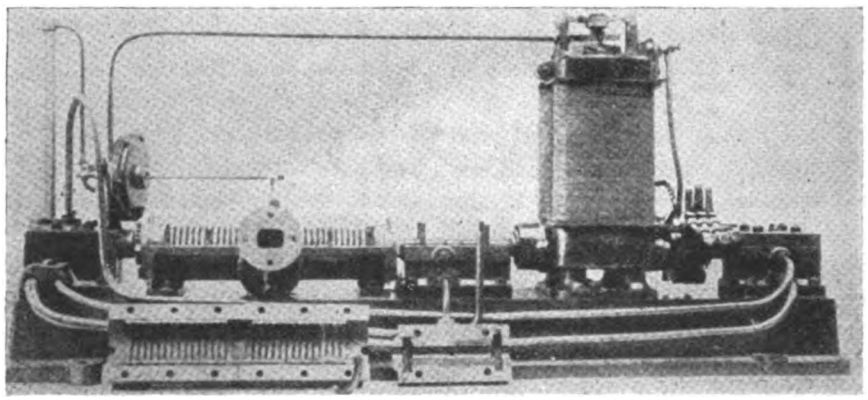

FIG. 2—VIEW OF PARSON'S TURBINE AND GENERATOR

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Another interesting feature of these turbines was the vacuum system employed for priming the lubricating system. As previously noted, one branch of the connection from the collar *A* was connected to the chamber above the oil reservoir, so that when the turbine was brought up to speed, the vacuum maintained in the chamber above the oil reservoir caused the oil to be forced up into this chamber by atmospheric pressure. The end of the turbine shaft was provided with a worm *W*, running in a closely fitting housing opening into the passage between the air chamber and the oil reservoir, so that as the oil rose in the passage it

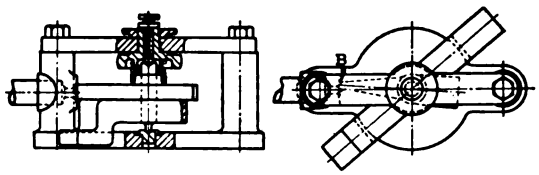


FIG. 3—MECHANISM OF PARSON'S GOVERNOR ABOVE FIELD WINDING

flowed into the worm pump which delivered it to the turbine bearings.

This old governor of Parsons has been described at length as it is beyond doubt the first governor employing centrifugal action on a fluid, rather than on solid weights.

The next fluid governor in which oil or liquid was the operating medium was suggested by Stumpf in 1903. As seen in Fig. 4, this governor consists of a centrifugal pump runner *C* on the end of the turbine shaft, which receives oil from an overhead reservoir *N*, and delivers the oil under pressure to a cylinder *I*. The pressure acting on the piston *K*, resisted by the spring *M*, causes the valve *H* to uncover successively one or more ports leading to individual nozzles of the turbine. As the pressure in the cylinder *I* increases,

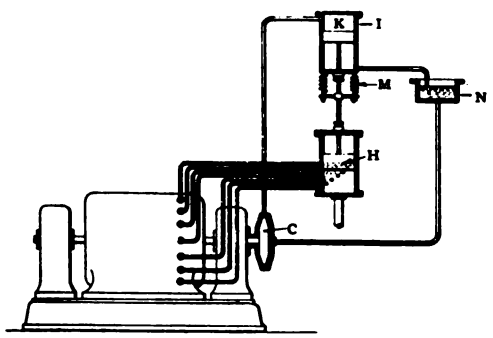


FIG. 4—A TURBINE CONTROLLED BY THE STUMPF GOVERNOR

the springs *M* are extended and the nozzles are shut off until the equilibrium is again established. The governor of Stumpf, while complete in the essential details of operation, was impracticable in the form shown as, of course, some other means would be required to keep the reservoir *N* filled with oil or other liquid to make up for leakage.

According to the patent records, the next fluid governor is that of Ehrhart in 1905. This governor, like the Stumpf governor, consists of a centrifugal pump connected to a chamber having a diaphragm as shown in Fig. 5, instead of a cylinder. The pump in this case is driven by a vertical shaft driven from the turbine shaft through a worm and gear, which permits placing the pump in the oil reservoir in a submerged position so that the entire oil supply of the turbine is available to make up for any slight leakage. It is interesting to note that, in addition to the centrifugal pump runner *A*, a segmental diaphragm *B* was provided, which permitted a part of the oil pumped by the centrifugal runner to escape for part of each revolution, thus causing fluctuations in the oil pressure in order to keep the entire governing mechanism oscillating, and so eliminating the friction of rest. Furthermore, the governor valve, which was of the piston type, was made double-seating, so that it would shut off either in the lower or the upper limit of its travel. The valve was so arranged that should the oil pressure fail for any reason, such as lack of oil in the system, the governor spring *D* would push the diaphragm *C* down all the way, thus shutting off the steam. In order to permit opening the valve for starting, the latch *E* was

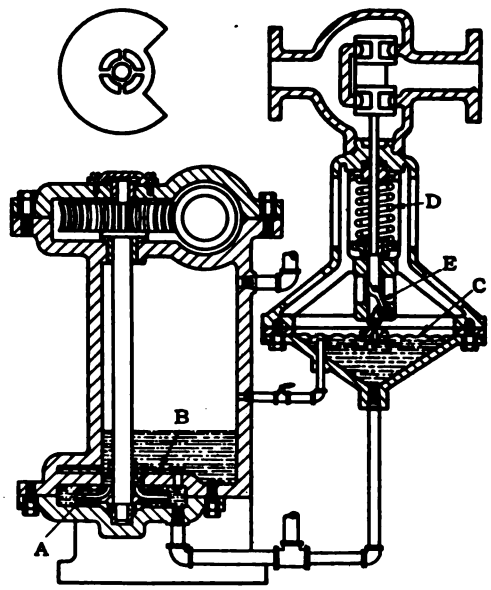


FIG. 5—EHRHART'S CENTRIFUGAL PUMP-TYPE GOVERNOR

provided for holding the valve open until the turbine got up to speed, after which the governing was done by the lower valve seats.

It is thus seen that in Ehrhart's governor, not only was a definite provision made for an ample supply of operating fluid, but provision was also made for varying the pressure to eliminate friction and to shut down the turbine in case of lack of oil, failure of the centrifugal pump, or breaking of the oil lines.

In the same year that Ehrhart developed his governor, Reichenbach filed an application for a fluid governor involving two new principles of operation, although he also showed one in which centrifugal force of the fluid in the impeller is the actuating means. These impellers are seen to be very wide for the work they have to do.

In the upper part of Fig. 6 is shown one of Reichenbach's arrangements in which a reservoir partly filled with fluid is supported on the end of a vertical shaft.

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Paddles are provided in the reservoir to insure that the liquid rotates with it. Entering through a hole in the top of the reservoir is a tube, the end of which is bent so that the open end of the tube faces the approaching liquid as the reservoir revolves. As is well known, a Pitot tube pointing against the stream, gives a pressure head equal to the velocity head of the stream, which of course is proportional to the square of the velocity. Thus the tube *D*, connecting with the cylinder, communicates a pressure proportional to the square of the speed of rotation. The pressure acting on the piston is resisted by a spring and controls the opening and closing of the valve *E*.

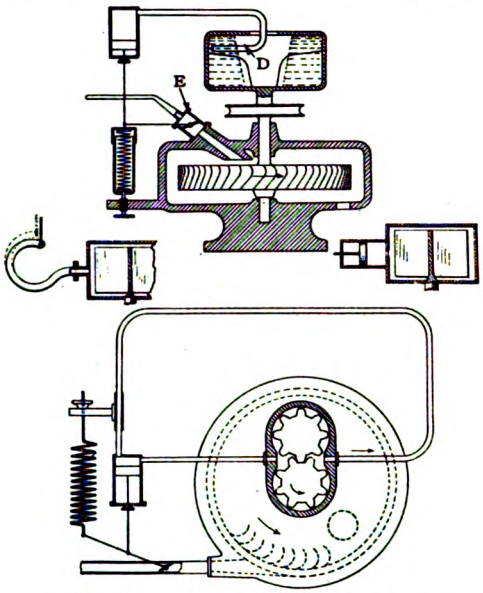


FIG. 6—THE REICHENBACH-TYPE GOVERNOR

In the lower part of Fig. 6, in place of the scoop arrangement shown above, a gear pump is employed which circulates the oil through the piping into the cylinder, and through an orifice and pipe back to the chamber. Since neglecting leakage, the capacity of a gear pump is directly proportional to the revolutions, and since the velocity is proportional to the square root of the head, and capacity is directly proportional to the velocity, it is evident that since the opening in the orifice is fixed, the pressure will be proportional to the square of the revolutions per minute of the pump. Thus with an ideal fluid, neglecting leakage, it is seen that a gear pump gives exactly the same result as a centrifugal pump or scoop.

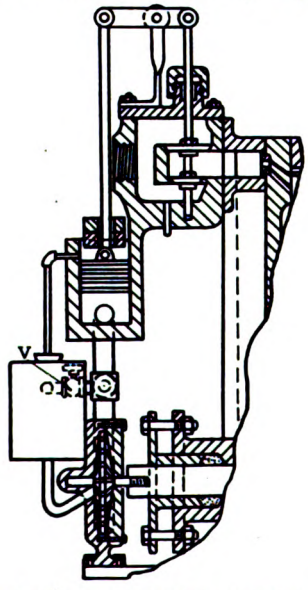


FIG. 7—CARTWRIGHT'S CENTRIFUGAL IMPELLER GOVERNOR

An oil governor patented by Cartwright in 1907 is shown in Fig. 7, in which a centrifugal impeller delivers oil under a piston, against the weight of the piston and connecting linkage. This patent is interesting in being the first instance in which cognizance is taken of air in the oil. The valve *V* is intended to be adjusted to permit a flow of oil back into the reservoir to prevent the impeller and governor from becoming air-bound.

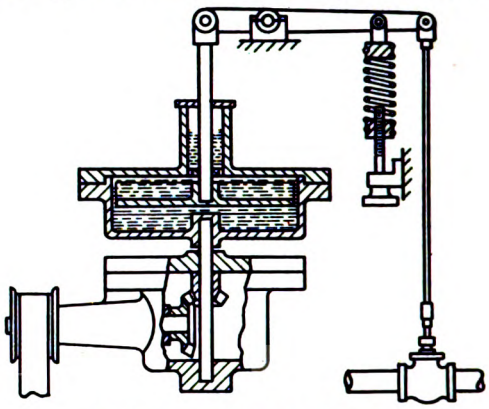

FIG. 8—SMOOT'S FLUID GOVERNOR

A different type of oil governor is shown in Fig. 8, suggested by Smoot. In this governor, oil is contained in a housing which is rotated by the engine, the impeller, or paddle wheel, (which is attached to the valve linkage) being held stationary. The lower portion of the rotating oil reservoir is fitted with paddles to cause the oil to rotate with the reservoir, and the upper portion of the piston or impeller attached to the valve linkage is also fitted with paddles to keep the oil

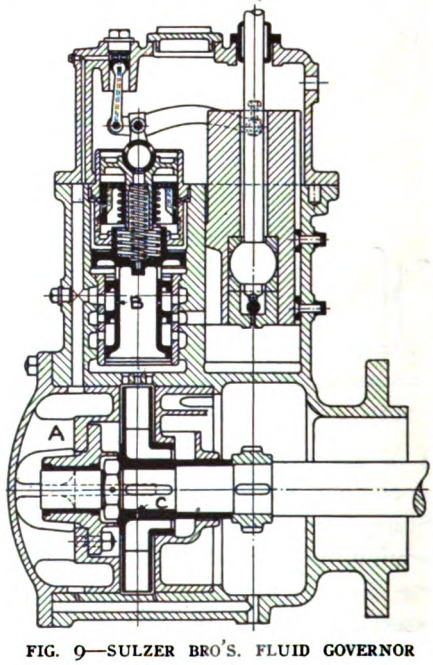


FIG. 9—SULZER BRO'S. FLUID GOVERNOR

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in them stationary. A surge chamber is provided over the rotating oil reservoir to insure the reservoir always being completely filled.

As the oil reservoir rotates, centrifugal force acting on the oil in the housing below the piston causes the pressure below the piston to decrease, causing the atmospheric pressure acting on the piston to push it down against the spring, thus moving the valve.

The objection to this type of governor is that the governing pressure is limited to that of the atmosphere, when the pressure at the center of the rotating oil under the piston decreases to zero, under which conditions, however, the pressure at the circumference is still atmospheric, so that the piston is acted upon by a pressure varying between atmospheric and zero. This necessitates a large diameter to give the power generally desired to operate a valve directly as shown.

Another governor employing oil as the medium was developed by Sulzer Bros. about 1911, and is shown in Fig. 9. The particularly interesting feature of this governing mechanism is that the centrifugal pump runner in this case is used as a relief valve, the relief pressure of which varies as the square of the speed of the pump runner. In this case, the oil for operating the mechanism is supplied to the chamber *A* by an independent pump under pressure in excess of that used for governing. The flow of oil through the pump runner is reversed, the high-pressure oil escaping through a leakage area *B* being supplied to the periphery of the pump runner. All oil in excess of that needed by the governing system, overflows from the center of the pump runner. Thus, since the pump runner is always full, the pressure maintained at the periphery is always equal to the head created by the centrifugal force on the column of oil in the runner. To insure the runner always being full of oil, particularly in starting, a hole is drilled in the end of the shaft opening into the chamber *A*, and radial holes *A* are provided in the impeller hub, which permit oil to escape from the chamber *A* to the center of the impeller.

*(To be Continued)*

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# The Relaying Problems of a Typical Large Interconnection

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IN this day of interconnections and more interconnections, one of the most important problems is the adequate and proper relaying necessary to permit the best use of such connections by both parties, and at the same time to provide the best protection for one system when trouble occurs on the other. When first discussed, and later tried out, it quickly became apparent that all that was demanded of the interconnection was not known, particularly with regard to the relaying of the tie.

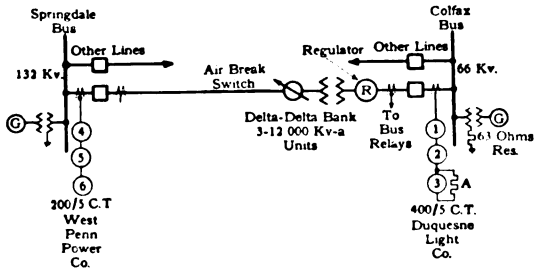


FIG. 1—SCHEMATIC DIAGRAM OF THE INTERCONNECTION

About a year ago, the Duquesne Light Company placed in service a 66 kv tie to its immediate neighbor, the West Penn Power Company. This connection was made between the Colfax power station on the Allegheny River, twenty miles above Pittsburgh, Pa., and the Springdale plant of the West Penn Power Company, two miles farther up the river.

A short while later the West Penn Power Company raised the voltage of their transmission bus at the Springdale power plant to 132 kv, and it was necessary for the Duquesne Light Company to install a 2:1 transformer bank on their end of this tie line to continue the interconnection. The 2:1 transformer bank consisted of three single-phase 12 000 kv-a units, connected delta-delta, installed outdoors, adjacent to the Colfax 66 kv switch yard. It was connected to the West Penn power station at Springdale by means of a two-mile, 132 kv transmission line on steel towers.

The same regulator was used after the 2:1 bank was installed as before. An electrically-operated, outdoor oil circuit breaker was installed in the line at the Springdale power plant, and one between the 2:1 bank and the 66 kv bus at Colfax power station, as shown in Fig. 1.

The relaying at each end of the line was the same in type, characteristics and settings; the only difference was that the ratio of the current transformers in the circuit breaker connected to the line at Springdale was 200:5 and the current transformers at the Colfax end were 400:5. This was made necessary by the difference in the transmission bus voltage of the two power stations.

### SHORT-CIRCUIT PROTECTION

The first plan was to relay this tie to trip out very quickly on minor cases of trouble on the tie or on either

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system. However, it developed, in discussing this point with the operating departments of both companies that, with trouble on either power system, it would be desirable to hold the tie in for a short period of time. Thus if the power company in trouble is able to clear its own fault quickly the tie is held in.

In case the power company in trouble does not clear its own fault in a reasonable time—some two seconds or more—the tie opens. The power system not in trouble is not disturbed to any great degree, and the power company in trouble must take care of itself without involving the adjacent company.

There are two groups of over-current relays on each end of the tie line, as shown in Fig. 1. One group is set for relatively slow operation, as shown in Fig. 2. The other group of relays are the fast relays, and are installed to clear a heavy short-circuit on the tie. The same scheme is used at the Springdale end, there

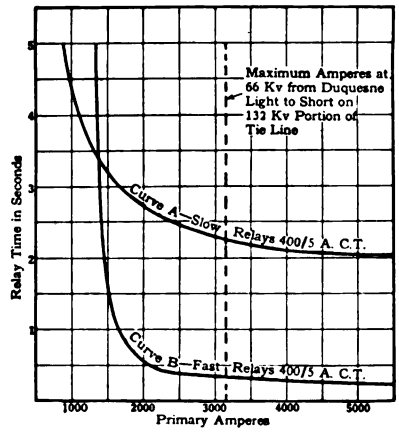
Maximum Amperes at 66 Kv from Duquesne Light to Short on 132 Kv Portion of Tie Line
Curve A—Slow Relays 400/5 A. C.T.
Curve B—Fast Relays 400/5 A. C.T.
Relay Time in Seconds
Primary Amperes
1000
2000
3000
4000
5000

FIG. 2—THE RELAY CHARACTERISTICS

being of course half as much current involved, since the voltage is twice as high.

The fast relays are set at a sufficiently high current value, as shown in Fig. 2 for the Colfax end, that they would be unlikely to operate unless the short-circuit was on the 132 kv portion of the tie line. The vertical dotted line on Fig. 2 indicates the maximum current that can be supplied by the 132 kv portion of the tie line. For this value of current both fast and slow relays would operate, but the fast relays would trip the circuit breakers on either or both ends. For other values of current the relays will operate as shown on Fig. 2.

There are certain locations such as a line fault on the 132 kv lines at Springdale, where a short-circuit could occur which would cause the tie to be opened without apparent necessity. It is felt that this chance is quite remote, for the Springdale power station would tend to hold up the voltage on its bus and less current would flow from Colfax. Therefore, in this case the fast relays operate more slowly, and very likely the Springdale line circuit-breakers would open before the tie would.

This method of relaying has worked quite satisfactorily. Upon one or two occasions when one power company was in trouble the tie has opened by means of the slow relays, thereby relieving the other power company of the disturbance. To date no severe short-circuit has been encountered which would cause the fast relays to operate. It is fervently hoped that no such condition will arise; however, in case it does the relays are standing by to operate quickly.

### GROUND RELAYING

The question of ground relaying was difficult only after the 2:1 bank had been installed. This problem had previously been relatively simple, and had been solved by using non-directional ground relays, set to select the important circuits feeding out of either power station.

However, when the 2:1 bank was installed, the problem of ground relaying became more involved, especially after it was decided to use a delta-delta transformer bank. The ground relaying consists of non-directional ground relays connected in the neutrals of the current transformer circuits of the circuit breakers at each end of the tie line. These ground relays protect only that portion of the line between their circuit breaker and the 2:1 bank, and are the same ones used when the tie was 66 kv throughout. They are set to operate very fast, as they do not have to select with any other circuits.

In addition to the ground relays, a signal circuit is installed on the tie line towers between the two power stations. This circuit is so interlocked that the opening of a circuit breaker on either end of the tie line will give a signal in the other power station, notifying the operator that the other end of the tie is open. With this signal scheme, when a ground on the line opens the circuit breaker at only one station, the operator at the other station will receive a signal. Knowing that the line is in trouble, he will immediately open the circuit breaker at his end.

This signal circuit between the two power stations is carried on the tower line that carries the 132 kv line. This circuit is also used for telephone communications between the two power stations.

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# Induced Voltages in Conductors

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IT is desirable for electrical engineers to have a description of magnetic lines of force and rules for the inducing of electromotive forces in conductors in electric power apparatus, which will apply to alternating-current generators, transformers, apparatus with sliding contacts, such as direct-current generators, and also to portions of electric circuits. Such a description applicable to the simplest types of circuits, is sometimes given in elementary books on electricity in a single sentence or two, but when application is made to all the cases required, additional explanations and restrictions are needed. The electromotive force induced in a short portion of an electric circuit by a magnetic field or by magnetic fields is referred to and computed in some of the best books and articles on electrical calculations. For a practical application, the e.m.f.'s in the portions of a circuit are added together until they give the e.m.f. of the complete closed circuit, which is found to agree with the measured value.

Examples of the calculation of the e.m.f. in short portions of circuits in authoritative publications can be given in almost any number desired. Alexander Russell, in "Alternating Currents" Vol. I, page 78, gives the self-inductance and mutual inductance in wires of assigned length, and therefore the voltages calculated for these portions of wires. He gives the voltages in the sides of a rectangle separately, and later adds them to give the voltage around the rectangle.

G. Carey Foster and A. W. Porter, in "Electricity and Magnetism", par. 300, under the heading "General Law of Induction—Electromotive Force", state that each element of a circuit which cuts a number of lines of induction is the seat of an electromotive force, and if the conductor does not form a closed circuit, a difference of potential is produced. From the above statement, and evidently referring to a circuit without sliding contacts, they derive the rule that, if the circuit is closed, the total electromotive force is equal to the rate of change of the flux of induction enclosed by the circuit, multiplied by the number of times the circuit surrounds the flux.

In the same book, par. 317, in describing Faraday's disc, it is stated that there is in each radius an electromotive force whose magnitude is calculated from the induction perpendicular to the plane of the disc, and from the speed of rotation, and if the brushes are not present this electromotive force charges the circumferential regions positively and the axial regions negatively.

If there is a magnetic field of intensity $B$, a unit magnetic pole placed in it will be subject to a force of $B$ dynes. The number of magnetic lines of force per sq. cm. of a plane perpendicular to the direction of the field is equal to $B$. If the value and direction of $B$ are known for every part of a certain area, the total number of lines of force passing through the area can be determined.

Two well-known expressions for induced e.m.f. in conductors are in use, namely,—

$$e = B\,l\,V \qquad (1)$$

where the induced e.m.f. in each portion of an electric conductor is proportional to the rate of cutting of magnetic lines of force across it, and,—

$$e = \frac{d\phi}{dt} \qquad (2)$$

where the induced e.m.f. in a complete electric circuit is proportional to the rate of change in the number of lines of force passing through it in a certain direction. Explanations and restrictions for the use of these equations will be given later. It is obviously not permissible to have descriptions of these equations such that conflicting results will be obtained.

Equation (2) does not refer to portions of electric circuits, and there are serious difficulties in applying it to apparatus with sliding contacts.

It is customary to speak of moving magnetic flux. Thus, the magnetic flux of a pole of a revolving field alternating-current generator is said to move with the pole and in so doing to cut the armature conductors and induce voltage in them, the same as if the conductors were moving past stationary poles. The fact that an e.m.f. is induced in a stationary conductor may be taken as a test for the motion of the magnetic flux. Since an e.m.f. is induced in a stationary conductor which is under the influence of alternating magnetic flux, the flux may be said to be moving across the conductor, each magnetic flux line taking up in succession the positions of the magnetic field, including the leakage field, surrounding the current.

Many books, particularly those on modern electromagnetic theory, do not speak of moving magnetic flux lines, and so a rule for induced voltage based on moving magnetic flux lines should be considered chiefly as a convenient rule which can be used for solving problems. Since this rule is found in many books on electrical engineering, it seems better not to give up the rule, but to adjust it or restrict it where it gives a wrong result, as described in this article. An additional advantage is that a quantitative description is given of conditions at the location of the conductor in which the voltage is being induced.

Taking equation (1), $e = B\,l\,V$, as a starting point, restrictions or explanations which are needed are as follows:—

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*Restriction I*—The magnetic flux density $B$ is the component of the magnetic field perpendicular to the length of the conductor. The velocity $V$ is the component of the relative velocity between the conductor and $B$, which is perpendicular to $B$ and to the conductor. The portion of the conductor of length $l$ is straight.

*Restriction* II—Equation (1) applies to infinitesimal conductors. The e.m.f. induced in conductors of finite cross-section is to be derived from the e.m.f.'s induced in the infinitesimal filaments making up the conductor. This restriction also applies to equation (2).

*Restriction III*—The magnetic field is not to be the resultant of component magnetic fields having velocities in different directions or of different magnitudes, if the use of the resultant field does not give the same result as the use of the component fields in the calculations. When the component fields are used, the e.m.f.'s from them are determined separately and then combined.

Restriction III is presented in this article, since it appears necessary because of such cases as a wire lying inside of a circular tube which carries alternating current, where the wire lies in zero resultant field and yet has an e.m.f. induced in it.

Another simple case in which Restriction III is required is where an electric circuit lies in a horizontal plane. Magnetic flux whose direction is upward is moving into the circuit across a certain part, and at the same time, magnetic flux whose direction is downward is moving out of the circuit across the same part. Both of these motions produce e.m.f.'s which add to each other, and both motions increase the total upward magnetic flux through the circuit. Yet the two fluxes, if equal, have a resultant zero and the part of the circuit considered lies in zero magnetic flux density.

It may be mentioned that in applying eq. (1), the velocity $V$ is not always the relative velocity between the bodies in motion, but a calculation is usually made of the number of lines which cut the conductor in a given time.

Most skin effect and proximity effect calculations are made by means of component e.m.f.'s, rather than by calculating the strength of resultant magnetic fields.*

Equation (2) can be derived directly from (1) for the case of closed metallic circuits which are subject to the restriction that they do not contain moving or sliding contacts. It seems safe to say that the only way in which the amount of magnetic flux passing through such a circuit can change is by the magnetic flux cutting across the conductor composing the circuit. If flux cuts across the conductor at a uniform rate for one second, the voltage induced in the conductor is, by eq., (1) equal to the amount of flux which has crossed in that time. This is the same as the rate of change of the flux through the circuit. No cases are given where the resultant field gives a different result from the component fields, with eq. (2), and so Restriction III does not seem to be required with eq. (2). Cases involving moving or sliding contacts between conductors being the only exceptions mentioned to the use of equation (2), the well known use of this equation in the calculation of electromagnetic waves is not involved. For such calculations reference should be made to publications on electromagnetic theory.

Let $W$ and $W_1$ be two very small wires arranged to form a return circuit. Each is surrounded by two copper tubes carrying $I$ and $-I$ amperes, alternating current, as shown in Fig. 1.

The induced e.m.f. in $W$ or $W_1$ per cm. is readily determined by means of eq. (2). Since the current producing the flux is alternating, the flux through the circuit $W$ $W_1$ is alternating and induces a voltage in it which can be expressed per centimeter, since conditions are symmetrical along the wires, and the end effect is negligible for long parallel conductors. If the thickness of the tubes is negligible, the induced e.m.f. is,—

$j \omega 2 I \log_h (b/a)$ abvolts per cm. .....(3)

where $\omega = 2\pi f$ and $f$ is the frequency.

The case of a tubular conductor is dealt with by Maxwell, in "Electricity and Magnetism", Vol. II, par. 683 and 684. After eq. (11) he states that the magnetic force within the tube, due to its own current, is

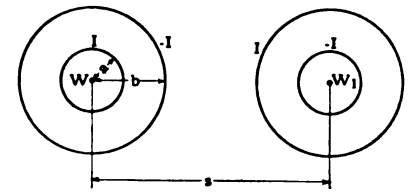


FIG. I—CURRENT CARRYING CONDUCTORS SURROUNDED BY COPPER TUBES

zero, and in eq. (18) he states that the vector potential in the direction of the axis is not zero but is a constant, its effect, including the effect of the thickness of the tubes, being given by eq. (22), which is in agreement with eq. (3) of the preceding paragraph.

Alexander Russell also gives a solution for a case similar to this, in "Alternating Currents", Vol. 1, p. 207. In calculating the e.m.f. induced in a wire inside a tubular conductor, flux produced by the current in the tube is taken to induce e.m.f. in the wire, the amount being in agreement with eq. (3).

It ought not to be possible to obtain any other value of induced e.m.f. than (3) by using eq. (1). But if a statement of eq. (1) given in many elementary textbooks of electrical engineering is used, a wrong result will be obtained. For instance, p. 59 of "The Magnetic Circuit" by V. Karapetoff, eq. (27), $e = B\,l\,V$ is given as a formula for electrical engineers to use in solving problems. For the case where $B$, $l$ and $V$ are mutually perpendicular, $B$ is given as the magnetic field density and $V$ as the relative velocity. If this formula as given be applied to wire $W$ Fig. 1, the field density $B$ and the e.m.f. will be zero, and the correct value of e.m.f. given by eq. (3) will not be obtained.

It is not advisable to say that eq. (1) is incorrect

*"Proximity Effect in Wires and Thin Tubes", by H. B. Dwight, *Trans. A.I.E.E.* 1923, p. 850.

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and not to be used, for it is reliable if suitably described and it is desirable for apparatus with sliding contacts and for portions of circuits. Accordingly a statement such as Restriction III should be included when giving Equation (1).

In determining the separate e.m.f.'s due to the component fields cutting $W$ the copper tubes should be divided into small elementary filaments. When frequency effects are not to be considered, the current may be considered to be uniformly distributed over the tubes. The thickness of the tubes being considered negligible, as before, every filament of the inner tube is at distance $a$ from wire $W$, and so each elementary current $i$ induces the same e.m.f. in $W$, namely,—

$$j\,\omega\,2\,i\,\log h\ (u/a)$$

counting flux up to a certain large distance $u$. All these e.m.f.'s are to be added together, giving a total,—

$$j\,\omega\,2\,I\,\log h\ (u/a)$$

Similarly, the e.m.f. induced in $W$ by $-I$ in the outer tube is,—

$$-j\,\omega\,2\,I\,\log h\ (u/b)$$

The sum of these is,—

$$j\,\omega\,2\,I\,\log h\ (b/a)$$

which is the same as (3). No matter how large a value of $u$ might be taken, the result would be the same.

In a similar manner, it can be calculated that the currents in the tubes surrounding $W$ induce zero total e.m.f. in $W$. The filaments of these tubes are at different distances from $W$, but the geometric mean of these distances is $s$ for both of the right-hand tubes.* If the variable distance be denoted by $q$, the average value of $\log h\ q$ is $\log h\ s$. The e.m.f. induced in $W$ by each elementary current $i$ in the right-hand outer tube is,—

$$j\,\omega\,2\,i\,\log h\ (u/q)$$

The total of all such e.m.f.'s is,—

$$j\,\omega\,2\,I\,\log h\ (u/s)$$

using the average value of $\log h\ q$. Similarly, the e.m.f. induced in $W$ by the right-hand inner tube is,—

$$-j\,\omega\,2\,I\,\log h\ (u/s)$$

The sum of these two quantities is zero.

Although the wire $W$ lies in a resultant magnetic field of zero density, it is cut by component magnetic fluxes travelling in different directions. Since voltage is induced in wire $W$, the region of zero resultant magnetic density inside the tube is not in as quiescent a state as a region remote from all currents, where no voltage would be induced in a wire. Outside of a tubular conductor the resultant field and the component fields usually give the same results, while inside the tube they do not.

By a procedure similar to that just described, the inductance of a circuit of two parallel seven-wire cables can be calculated.** It does not seem feasible to use the resultant magnetic field in solving the cable problem.

The permeability of iron is in accordance with the resultant magnetomotive force applied to the iron. If an iron pipe be placed around the wire $W$, Fig. 1, but inside the smaller copper tube, the resultant magnetomotive force at the iron is zero, since the resultant field in air was zero. There will be no increase in e.m.f. induced in $W$ because of iron in this position.

If an iron pipe be placed around the smaller tube, and inside the larger, and concentric with them, the resultant magnetomotive force available to send flux around the pipe will be $4\,\pi\,I$ and the amount of flux can be determined by using a saturation curve or permeability curve of the iron. The increase in flux will be added to $\phi$ if eq. (2) and the resultant field are used to calculate the e.m.f. induced in $W$.

If the wire and inner tube be replaced by a seven-wire cable for each side of the circuit, the cables carrying $I$ and $-I$, and if the same iron pipe as in the preceding paragraph be placed around one cable, the same increase in induced e.m.f. will be produced, provided there is sufficient clearance between the cable and the inside of the pipe to keep local effects due to the individual wires of the cable negligible, thus keeping the resultant magnetomotive force uniform at all parts of the pipe. This means that the component fields are used to find the inductance of the cable in air, and the resultant field and eq. (2) are used to find the increase in inductance due to the iron.

This does not involve any conflict between the two methods. Either method should give the same result for the entire problem if suitable calculations were available to take care of the lack of symmetry encountered.

The core of a transformer is treated in a somewhat similar manner, the resultant flux and eq. (2) being used. However, in considering eddy currents and losses in the copper conductors, the latter are divided into infinitesimal filaments, and the component magnetic fields are used.

It is not satisfactory to have the present lack of agreement as to rules for calculating induced voltages. Different books state the rules in different ways. It is only occasionally that the rules are found to be contradictory, as in the case described in this article. But quite frequently the rules are stated in incomplete fashion, so that a reader is not given definite information for certain practical problems. In some books, no direct statement is given as to portions of circuits or circuits with sliding contacts. In others, the $d\phi/dt$ rule, (eq. 2) is used to obtain the e.m.f. induced in a bar sliding along two wires of infinitesimal cross-section, but instructions are not included for the case where the wires have a large section, or where there are several wires in parallel, and the main path of the current in the stationary conductors is quite different before and after motion of the bar, thus giving rise to doubt as to what value of the flux through the circuit, to use in the calculation.

*J. Clerk Maxwell, "Electricity and Magnetism", Vol. II, p. 296, par. (7).

**See the Appendix of "Constant-Voltage Transmission", by H. B. Dwight.

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A suggestion may be made as to one possible way to unify these matters. It might be possible to draw up a set of rules, which would be complete and definite enough to use for the solution of the different types of problems encountered by electrical calculators, radiation effects not being included; which would involve comparatively simple mathematics, such as is involved by the rules discussed in this article; and which would be capable of proof according to modern electromagnetic theory. If this were done, there would be only one fundamental basis for electrical calculations, whether of advanced physics or of electrical engineering. The rules would become propositions, and when published would be given complete with the necessary qualifications. There would not then be almost as many different ways for applying or repudiating a rule for solving problems as there are types of problems or individual writers, but there would be one standard procedure.

# The Grid Glow Tube Relay

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RELAYS of widely varying descriptions are needed in the commercial engineering field. In some cases they must be capable of carrying large amounts of power, perhaps hundreds of amperes. In such relays the control current is usually several amperes and the sensitivity is low. Other relays control smaller amounts of power and the control current required is proportionally decreased. The most sensitive of these relays will control approximately 10 000 times as much power as is required to operate them. This figure is called the power amplifying factor, or simply amplifying factor, of the relay. Those mechanical relays having an amplifying factor as high as 10 000 are very expensive and not generally used. The more common ones have an amplifying factor of something like 500.

The relay which will be described in this paper has an amplifying factor, under certain conditions, of 100 000 000 or even more. As a matter of fact, the amplifying factor is adjustable within wide limits. It can be made high or very low to suit the conditions at hand.

## GENERAL DESCRIPTION

The grid-glow relay consists essentially of a tube, resembling an ordinary radio vacuum tube. Like the latter it contains an anode, cathode and a grid. The cathode is a cylinder of aluminum. Inside the cylinder is the anode and grid, both made of heavy nickel wire. The grid is so shaped and placed that the anode is enclosed by it.

The relative positions of anode, cathode and grid are shown in Fig. 2. The tube is filled to a suitable pressure with one of the inert gases, such as argon, neon or helium. There is no filament. Current passes in the form of a glow discharge, between cold electrodes.

## FUNDAMENTAL OPERATION

The simple circuit in Fig. 3 illustrates some of the more important characteristics of this tube. $T$ is a transformer which steps the voltage up to about 440 volts. This voltage is impressed between anode $A$ and cathode $C$ in series with a resistance $R$. The resistance $R$ is essential, as the glow discharge is unstable, i.e., the resistance decreases as the current increases. It is evident, therefore, that the discharge will pass instantly from a glow to an arc and the tube will be destroyed, unless a resistance is used to limit the current to a suitable value, say 10 milliamperes. This requires about 5000 ohms, which may be in the coil of a mechanical relay, if one is used.

By means of the switch $S$ the grid $G$ may be connected to the anode through a variable high resistance $r$. If $S$ is open—in other words if the grid is disconnected and carefully insulated from the anode—a high voltage $E$ is required to cause a discharge. Under favorable conditions 600 volts alternating current will not cause a current to flow when the grid is insulated.

FIG. 1—THE KNOWLES GRID GLOW TUBE

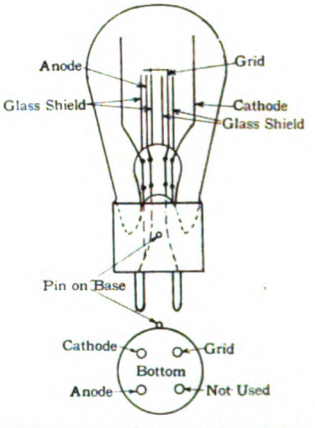


FIG. 2—A DIAGRAMATIC SKETCH OF THE GRID GLOW TUBE

If the switch $S$ is closed and $r$ is adjusted to 100 megohms, for example, the discharge will occur at about 525 volts. As the resistance $r$ is decreased further, the breakdown voltage decreases as shown in Fig. 4. At all

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points on or above the curve current is passing between the anode and cathode, and at all points under the curve there is no current. The current which flows in the control circuit (through $r$) for values of $r$ equal to or greater than 10 megohms, is approximately one millionth of an ampere. For lower values of grid resistance the grid current increases until the limit is reached where the grid is connected directly to the anode and carries practically all the current (10 milliamperes, or whatever current is allowed to flow in the anode-cathode circuit).

Several applications for the tube are suggested by the shape of the curve in Fig. 4.

### CONTACTLESS RELAYS

Probably the most obvious application is its use as a semicontactless relay. In many instruments, such as temperature control apparatus, a very delicate contact is made, which must carry sufficient current to operate a relay. Such contacts usually give trouble due to arcing, freezing shut or poor contact. If the grid-glow tube is used, however, and this contact merely alters the resistance of the grid circuit, the tube and not the contacts will carry the control current. In some cases

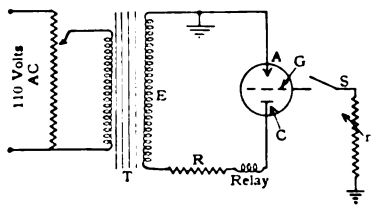


FIG. 3—A SIMPLE GRID GLOW TUBE CIRCUIT

the tube will carry the field current of a small motor directly, thus eliminating the mechanical relay entirely.

An almost endless number of applications of this nature will suggest themselves to engineers familiar with apparatus employing such delicate contacts.

### CONDENSER CONTROL

Instead of the resistance $r$ in Fig. 3, a condenser action can be used as a control. If the alternating-current impedance of the condenser is plotted against breakdown voltage a curve somewhat similar to Fig. 4 is obtained. This opens another field of possibilities.

For example, assume a tube with 440 volts alternating current, 60 cycles impressed on the anode-cathode circuit. Fig. 4 shows that an impedance of 45 megohms or less will cause the relay to operate. To give such an impedance a condenser would have a capacity of

$$C = \frac{10^{12}}{2\pi f X} = 580 \text{ m. m. f.}$$

where $f$ is the frequency, and $X$ the impedance in ohms.

Tests, however, show that a condenser of 10 micromicrofarads is ample to cause operation at this point on the characteristic. The explanation lies in the fact that the small current which flows in the grid circuit just prior to operation of the relay is oscillating at a frequency which depends on the constants of the grid circuit. Under certain conditions this frequency is several thousand cycles per second, and a capacity of one micromicrofarad is enough to cause operation.

The constants of the grid circuit are easily controlled, thus making it possible to adjust the tube to any desired sensitivity. In practice a variable air condenser, such as used in radio sets, can be used for adjusting to the desired sensitivity, and the capacity of some moving body to a fixed metal plate may supply the balance required to actuate the tube.

A small plush lined tray is often used by jewellers for exhibiting rings, etc. Suppose the under side of this tray be covered with tin foil and a watch is placed on the tray. A hand held within one inch of the tray will, in conjunction with the tin foil, form a condenser of approximately ten micromicrofarads and a relay circuit can easily be adjusted to operate on this capacity. A thief could therefore be detected before he had even touched the object. Instead of the tray, connections can be made to door knobs, metal window frames, or in fact any insulated conductor that might be touched by an intruder.

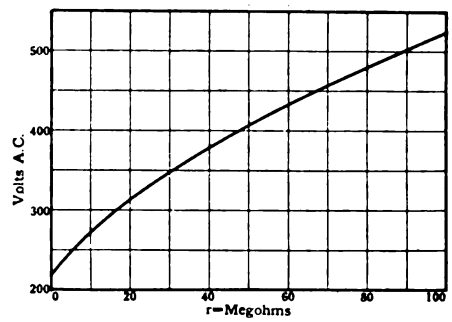


FIG. 4—BREAKDOWN VOLTAGE CHARACTERISTIC OF GRID GLOW TUBE

Other less spectacular examples of condenser control are:—

1—Depth or level gages for water, oil, etc.
2—Specific inductive capacity meter.
3—Counting items in mass production.

Up to the present only those conditions where the grid is self-energizing have been considered. In other words, the grid assumes a potential due to its position and electrical condition with respect to the anode and cathode of the tube. This potential is due to a charge which accumulates at a certain rate. The rate of supply being limited, the actual potential assumed by the grid varies inversely with the rate at which the charge is allowed to leak off. This gives us one form of control which has been illustrated in the first part of this article.

In these instances, the operation is not that of a relay in the ordinary sense. It might better be termed a very sensitive detector, a device which detects very small changes in the constants of the grid circuit. When these changes exceed certain definite limits the tube suddenly responds and passes a definite current. In all cases the action is discontinuous—in other words, with a fixed voltage applied, no current passes until a critical condition is reached. At this point the tube suddenly glows, which is evidence of its operation.

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IMPRESSED VOLTAGE CONTROL

The more common conception of a relay is a device which operates on a small amount of energy from one source, and thus controls a larger amount of power from another entirely separate source. The grid-glow tube will operate in precisely this manner.

A circuit using this form of control is shown in Fig. 5. $E_p$ is a source of voltage applied to the anode and cathode of the tube, in series with the coil of a mechanical relay. $E_G$ is a separate voltage applied to the control or grid circuit of the tube through a resistance $R_G$. This should be several million ohms. If the voltages are alternating the instantaneous polarity on one half of the cycle, as shown in Fig. 5, is considered positive.

The relation between $E_p$ and $E_G$ is shown in Fig. 6, where both voltages are 60 cycle r.m.s. values. At all points on or above the curve current is passing, and at all points under the curve there is no current. Suppose,

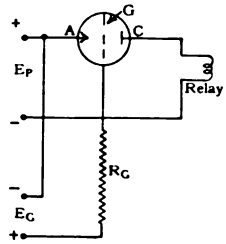


FIG. 5—THE GRID GLOW TUBE IN A RELAY CIRCUIT

for example, $E_p$ is 200 volts. $E_G$ can be anything less than + 125 and the tube will not pass current, but the instant this limit is exceeded the tube functions. $E_G$ can then increase within reasonable limits without further affecting the current flowing in the anode-cathode circuit.

If $R_G$ in this instance is 10 megohms, the current flowing in this circuit is approximately two microamperes at 125 volts, or 0.00025 watts. The available output is 0.025 amperes at 100 volts, or 2.5 watts and the amplifying factor is accordingly 10 000. If $R_G$ is increased, the curve in Fig. 4 is shifted upward but remains essentially parallel to the one given. The amplifying factor also increases rapidly with increased grid resistance. Also as $E_p$ is increased and $E_G$ decreased—in other words, as the operating point $p$ approaches the $E_p$ axis—the amplifying factor increases, reaching infinitely high values, and decreases again as $E_G$ increases with reversed polarity. If $E_p$ is less than 325 volts, a positive grid voltage is required to cause breakdown, whereas if $E_p$ is greater than 325 volts, current is normally passing and a negative grid voltage is required to stop it.

It is therefore possible, by employing suitable voltages of the proper polarity, to use the tube either as a direct or as an inverse relay, and at the same time vary the sensitivity within wide limits by selecting the operating point on the curve, and the grid resistance to be used.

Where reversible operation is desired alternating voltage must be used. If direct current is used a certain grid influence will cause the tube to operate but, unlike alternating current operation, it continues to pass current even after the influence has been removed. The current can be stopped by momentarily removing the plate voltage.

Ordinarily this might be considered a disadvantage, but really it permits some valuable operations that cannot be secured with ordinary relays. For example, influences of short duration, such as voltage surges, can be detected or made to actuate mechanical relays. If the

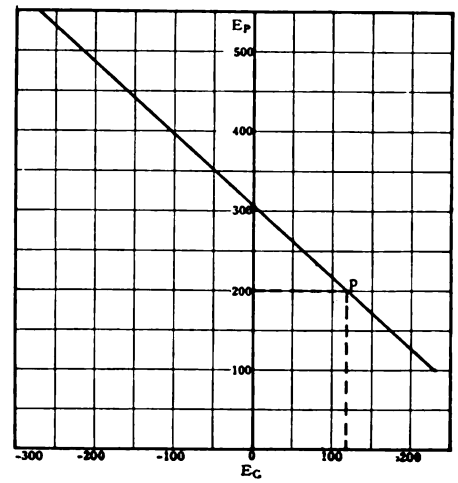


FIG. 6—CRITICAL FUNCTIONING VOLTAGE, CHARACTERISTIC OF THE GRID GLOW TUBE

operation is that of recording, the recording mechanism can momentarily interrupt the voltage and reset for the next surge.

MISCELLANEOUS APPLICATIONS

Many other applications are possible, such as:—

1—Detection of impurities in solutions or in water in so far as they affect conductivity.

2—Detection of deposits of moisture or dirt on normally insulating dry surfaces.

3—As a relay in conjunction with a simple photo cell or selenium cell.

4—Measurement of high resistance.

5—Counting production items.

6—An adjustable voltage indicator, as suggested by Fig. 4.

It is evident that the grid-glow relay has numerous applications in the engineering field. Undoubtedly some very important ones have been overlooked in this discussion. It is intended merely that the facts here given will enable the individual engineer to visualize its possibilities in the solution of his own problems.

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# Graphical Flux Mapping

## II--Fields of Non-Salient Pole Synchronous Machines

J. F. CALVERT and A. M. HARRISON

This is the second of a series of articles on graphical flux mapping. The first article, which appeared in the March issue of THE ELECTRIC JOURNAL, gave a brief summary of the various methods which have been used in flux studies, the fundamental theory of the graphical method with several examples and simple solutions, and a fairly complete bibliography of the published work on flux plotting for electrical machines.

PROBABLY the most evident feature in the preceding article, was the usefulness of type cases or similar drawings to facilitate the solution of any flux mapping problem. In this article, fields will be shown for turbine generators when only the rotor winding is excited.

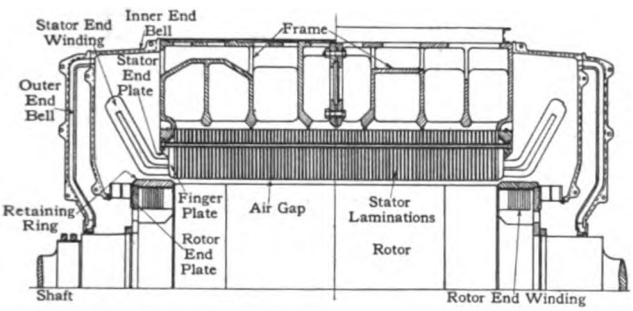


FIG. 11—CROSS-SECTION OF THE UPPER HALF OF A TURBINE GENERATOR

A complete turbine generator with the parts marked in accordance with the discussion below is shown in Fig. 11. The description of the flux distributions will be prefaced with a few drawings illustrating the fields of conductors in slots. These plots will have special significance later in the larger and more complicated solutions to follow.

FIELDS OF CONDUCTORS IN RECTANGULAR IRON SLOTS

Figures 12, 13, and 14 were first obtained by drawing the fields due to each conductor alone and then superposing these distributions. It should be observed that in Fig. 12, the orthogonal lines representing equal ampere turns in the slot space above the two conductors do not necessarily indicate an equal division of ampere turns along a flux tube between the conductors.

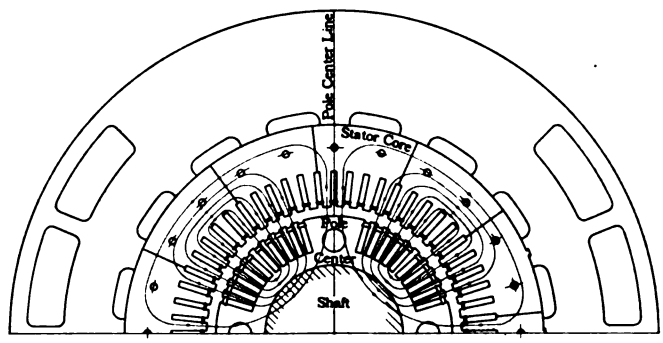


FIG. 15—A DIAGRAMATIC SKETCH OF A NO-LOAD FIELD FLUX

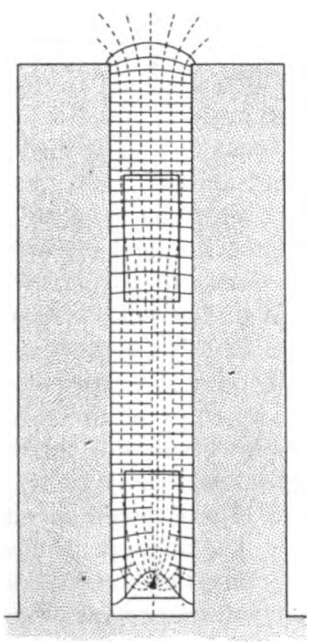

Fig. 12—Currents in the same direction.

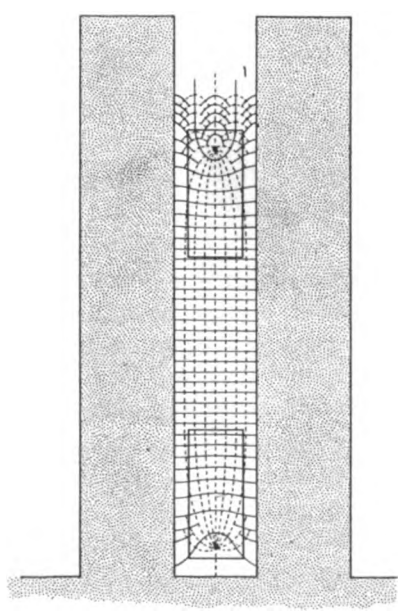

Fig. 13—Currents in opposite direction.

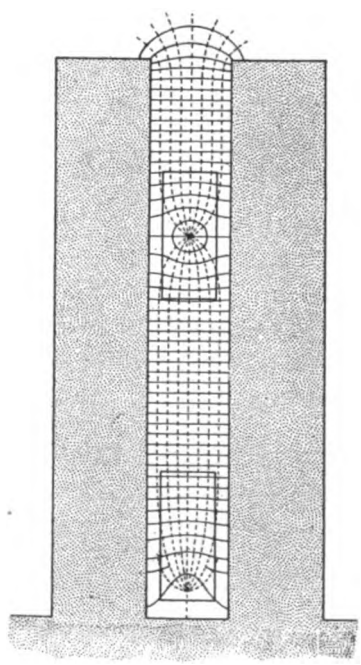

Fig. 14—Currents in opposite direction—current in the upper conductor is twice that in the lower.

FIG. 12, 13, 14—FLUX DISTRIBUTION IN SLOTS CONTAINING TWO CONDUCTORS

It is only necessary to apply the fundamental relation between the incremental reluctances and the ampere turns* to justify this conclusion. In Fig. 13, the mag-

*Derived in the first article.

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netomotive forces of the two conductors practically cancel in the upper portion of the slot. Half of the upper conductor cancels or balances the lower conductor in Fig. 14.

### FLUX IN THE AIR-GAP AND IN THE ROTOR IRON WITH ONLY THE FIELD EXCITED

In the following figures, other than the diagrammatic sketches and sectional drawings of larger fields, the flux has been plotted strictly on the basis of the

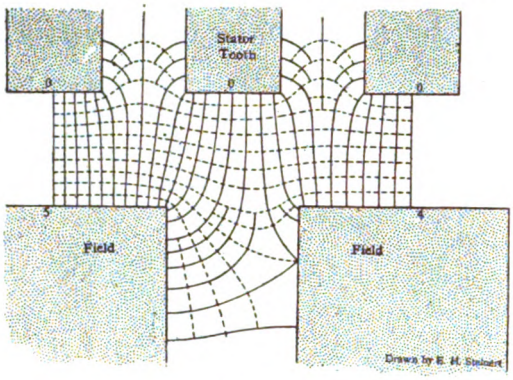


FIG. 16—FLUX DISTRIBUTION IN THE AIR-GAP ADJACENT TO THE ROTOR POLE CENTER, FIELD ALONE EXCITED

magnetomotive forces indicated. That is, the effects of damping currents on higher harmonics have not been considered.

The paths of the rotor field flux are shown diagramatically in Fig. 15. Fig. 16 shows the flux distribution in the air-gap and rotor slot adjacent to the pole center. The rotor conductors are well below the air gap; and the differences in the numbers on the iron parts have been chosen such that they are proportional

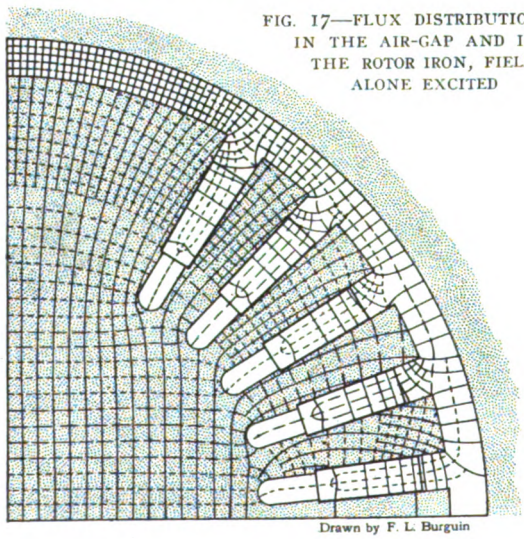


FIG. 17—FLUX DISTRIBUTION IN THE AIR-GAP AND IN THE ROTOR IRON, FIELD ALONE EXCITED

to the m.m.f. differences between the corresponding surfaces, and in the directions from the higher toward the lower numbers. The approximate locations of the orthogonal lines are then easily established, and the flux lines drawn at right angles to them. Plainly, the 4 line must meet the 4 surface, producing a "singular point"* at the junction. The distribution in the neighborhood of such a point has been described in the previous article. With such data established, the field may be balanced to give a certain degree of accuracy as shown.

The work shown in Fig. 16 is extended in Fig. 17 to illustrate the flux distribution both in the air-gap and in the rotor iron, when the rotor is excited alone. The field in the non-magnetic parts was drawn on the assumption that the iron had practically infinite permeability relative to that of the air. This established the flux entering and leaving the iron surfaces. Then the field was plotted within the iron on the basis of uniform permeability. This gave the location of the ampere-turn lines in the iron, and the conductors from which these lines emanate can be established. First consider the conductor in the slot adjacent to the pole center. There must be one orthogonal line from the m.m.f. center in the conductor to the base of the slot. There is one orthogonal line in the iron going each way from this singular point. From the direction of the

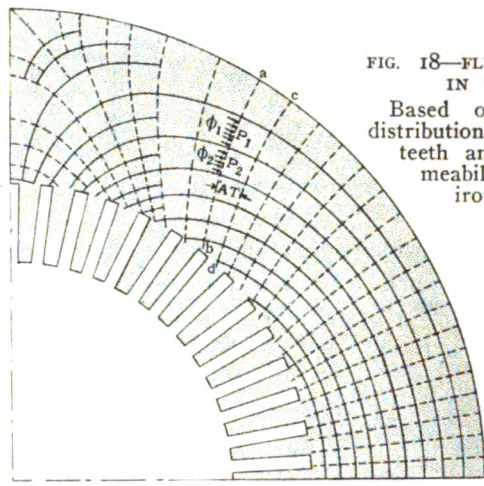


FIG. 18—FLUX DISTRIBUTION IN THE CORE
Based on a sinusoidal distribution at the base of teeth and uniform permeability in the core iron.

flux lines, it can be seen that the ampere turns of the conductor in the slot nearest the pole center are effective on the paths from just below the 4 line of the gap, the right hand surface of the slot, and the orthogonal line in the iron which proceeds to the left from the singular point in the base of the slot. Similarly, by tracing out the directions of the flux paths between the pole center and the second rotor slot from the left, it will be found that there is a sort of sphere of influence for the next conductor which fits outside the first one considered. The third conductor is effective outside of the second, etc., down to the center line between poles. The last conductor, i.e., adjacent to the center line between poles, must carry the flux in the stator iron. This division of the ampere turns is brought out in Fig. 17 by showing the orthogonal lines from successive conductors alternately in dashes and then in dots.

Certain approximations are necessary at the outer left corners of each of the rotor slots in Fig. 17 to take care of the fact that the iron has a finite permeability. No effort has been made to plot these sections on the basis of an absolutely fixed ratio of iron to air per-

*This term was adopted from an article by Prof. A. D. Moore. (See bibliography at the end of the previous article).

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meability, as this did not seem to be of primary importance.

### FLUX DISTRIBUTION IN THE STATOR CORE WITH ONLY THE FIELD EXCITED

The flux in the core, Fig. 18, also has been plotted on the basis of uniform permeability. A drawing similar to Fig. 17, but with stator teeth present, might be used to determine the flux entering the stator. The flux must pass nearly radially through the armature teeth, though in considering the densities in the iron, some method[12] or approximation[13] should be made to consider the fringing into the teeth from the slots. These methods might also be applied to the rotor in the calculation of magnetization curves. However, the flux entering the core at the base of the teeth can be fairly readily determined. When this distribution is fixed and it is assumed that the flux leaving the back of the core may be neglected, then the boundary conditions have been established. If symmetry exists within every pole pitch, as is the case under the no-load, field-excited condition, further relations are known. The core flux will cross the extension of the center line between poles at right angles and the density will vary inversely as the distance from the rotor or shaft center line. Also the field will be symmetrical about the extension of the rotor pole center line.

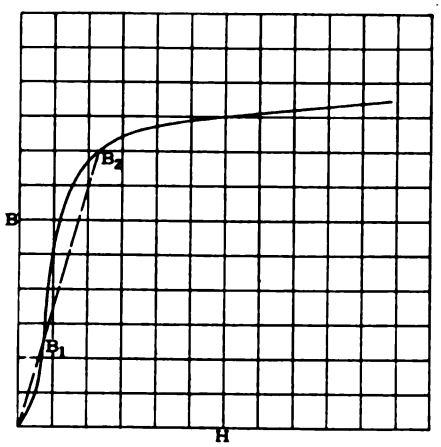


FIG. 19—A NORMAL SATURATION CURVE FOR CORE IRON

In plotting the field for Fig. 18, a sinusoidal variation in density was assumed for the flux entering the core across some circumferential line just behind the stator slots. The field within the core was plotted by extrapolating from the known boundary conditions. This has been described in the first article, and therefore, will not be considered in further detail here.

At this juncture, it would be well to note some of the factors involved by the assumption of uniform permeability. Fig. 19 shows a normal saturation curve for armature iron. If the densities in the iron parts range from $B_1$ to $B_2$, then the assumption of uniform permeability is a reasonable approximation. If the densities in a considerable portion are greater than $B_2$, or perhaps less than $B_1$, appreciable errors are introduced. The general shape of the flux path is also an important factor. Where the densities are greater than $B_2$, which is the more likely source of discrepancy, the true distribution will have distinctly more uniform densities than would exist with uniform permeability, because the permeability will decrease with increase in density in any portion.

### FLUX DISTRIBUTIONS IN THE END ZONES, WITH ONLY THE FIELD EXCITED

The field in the end zone is always influenced to a great extent by the relative degrees of saturation in the different parts of the rotor retaining ring and rotor end plate. When the field is excited by itself, the condition in these iron parts is the predominant influence acting on the inner end-bell air space. The retaining ring and the rotor end plate form a magnetic short-circuit on the field, and it can be only after these are saturated that flux leaves the rotor at all. An exploration with a compass reveals the fact that the flux close to the surface of the retaining ring is almost parallel to the surface (except near the air-gap). It follows that the orthogonal surfaces must pass almost perpendicularly through the iron. Consequently, the compass exploration may be used to estimate the flux distribution within the retaining ring iron, Fig. 20. This method cannot be applied to the rotor end plate, because here the flux in the air stands almost at right angles to the iron surface. However, the boundary conditions for the field in the rotor end plate are known. The field is parallel to the pole center line at this boundary of a pole quadrant, and the flux meets the center line between poles at right angles. The way it enters the end plate can be found from the retaining ring drawing. The end-plate flux distribution can be obtained by extrapolating from the field in the ring.

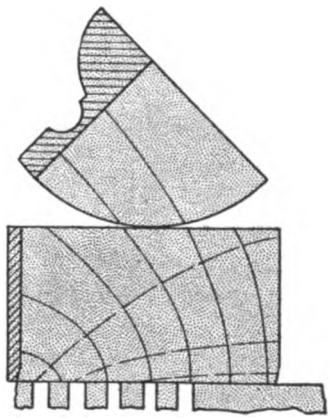

FIG. 20—THE FLUX DISTRIBUTION IN THE ROTOR RETAINING RINGS FIELD ALONE EXCITED

The orthogonal, or ampere-turn lines, are drawn at right angles to the flux paths. These start out from the rotor slots, and can be identified with the corresponding m.m.f. sources. The densities and ampere turns per inch in various parts of the ring can be cal-

[12] "Graphical Determination of Eddy and Laplacien Magnetic Fields" by Th. Lehman.—Revue Generale de 'Electricite'.—Sept. 15, 1923.

[13] "A Graphical Determination of Ampere Turns for Trapezoidal Teeth Sections", by J. F. Calvert, A.I.E.E. Journal, Jan. 1927.

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culated on the basis of the drawing and an approximate check on the field thus obtained.

This method of flux mapping is somewhat limited in application, because it is not purely an analytical scheme. However, there is one feature of the distribution shown in Fig. 20, which is quite important, since it will assist greatly in estimates made on other machines. The ampere turns are nearly all required for the field in the tapered section, and the flux travels almost axially across this section. Since a pronounced taper (such as the one shown) is a fairly general thing in commercial design, this condition in the flux field is typical, and may be used as a start in estimating similar fields in other machines.

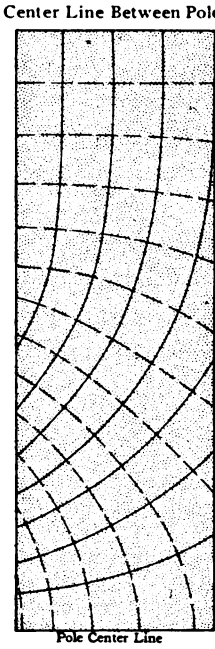


FIG. 21—FLUX DISTRIBUTION ABOVE THE STATOR END BELL IRON, FIELD ALONE EXCITED

The distribution of the flux in the end-bell iron presents a problem which is quite similar to that introduced by the retaining ring, except that saturation does not seem to enter into the field of the end bell iron. The end bell acts as a magnetic shunt or parallel path on the frame, and hence, indirectly, on the back of the stator core. The flux distribution just above the cylindrical surface of the end bell may be found by compass readings, Fig. 21. This field, if assumed to be the distribution in the iron, can be extrapolated over the end surfaces of the bell as was done for the rotor end plate. There is a marked difference in the fields shown in Figs. 20 and 21. The latter has almost perfect rectilinear squares, indicating fairly constant permeability, and relatively low densities, while the distribution in the former drawing does not give rectilinear squares and shows a high degree of saturation.

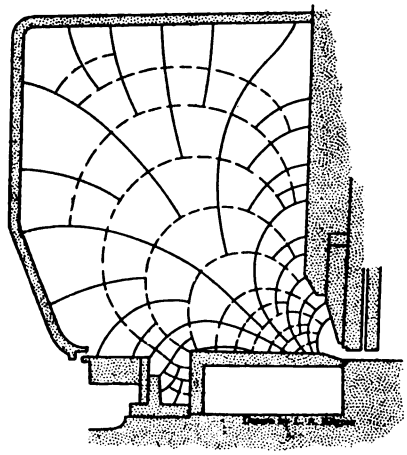

FIG. 22—FLUX DISTRIBUTION IN THE AIR WITHIN THE STATOR END BELL, FIELD ALONE EXCITED

This practically completes the consideration of flux distributions for the open-circuit voltage condition in turbine generators. However, an attempt has been made to estimate the field for the air space within the inner end bell. This field is shown in Figs. 22 and 23. It involves a number of assumptions and approximations; to wit,

1—The field is drawn only for the center plane of the rotor pole. This limit is necessary in order that the flux remain in one plane.

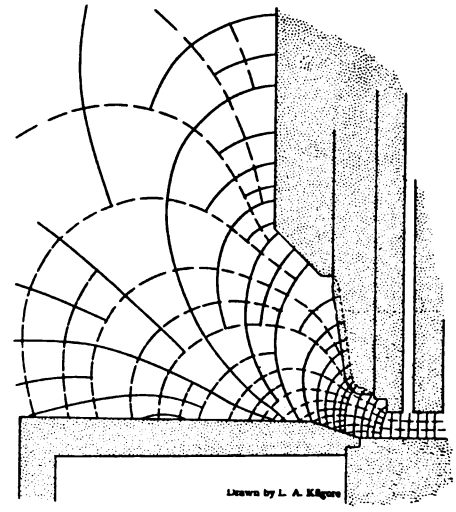

FIG. 23—FLUX DISTRIBUTION IN REGION OF THE FINGER PLATE IN FIG. 22

2—Uniform depth of section is assumed in the direction perpendicular to the plane of the drawing instead of considering that the incremental depth varies directly with the radius from the center line of the rotor shaft. This is necessary to permit the use of rectilinear squares.

3—The retaining ring flux distribution (similar to the one shown in Fig. 20) has been found in order to establish the distribution of the orthogonal lines at the outside surface of the retaining ring.

4—No saturation in the armature, and an equivalent continuous finger plate outline are assumed. (The equivalent finger plate outline has been approximated from Fig. 24, wherein a straight line iron surface is found which gives approximately the correct average reluctance for the paths in Figs. 22 and 23).

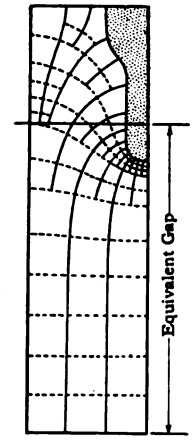


FIG. 24—FLUX ENTERING THE STATOR FINGER TOOTH FROM THE ROTOR

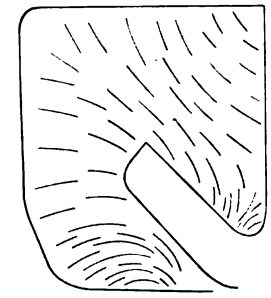

FIG 25—FLUX WITHIN THE END BELL

Determined by iron filings with field alone excited at twice normal field current. This was traced from a photograph of the filings.

Fig. 25 shows the same flux distribution obtained from iron filings. The difference in the outer parts is largely due to the ampere turns required for the stator iron and end bell.

*(To be continued)*

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# Phase-Angle Control Under Load

## By Means of Transformer Tap-Changing Equipment

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THE phase displacement between two parallel transmission lines feeding a common load, or between two generating stations in parallel, introduces a problem which is becoming increasingly important to central stations having extensive transmission networks, or which are interconnected with other stations. This has resulted in the need for a new type of apparatus—equipment for regulating the phase displacement between two parts of a circuit while under load.

The simplest type of interconnection is provided when two systems are connected together by means of a single line. If the system voltages vary with respect to each other, or even if the voltages of the two systems are the same with respect to each other, transformers provided with means for changing the voltage ratio under load may be inserted in the line to control the wattless power interchanged. The actual power transferred from one system to the other is, of course, a function of the relative governor settings and is not controlled by changing the ratio of the transformers in the line. Transformers provided with equipment for changing taps under load to provide voltage control under load are commonly used in this application.

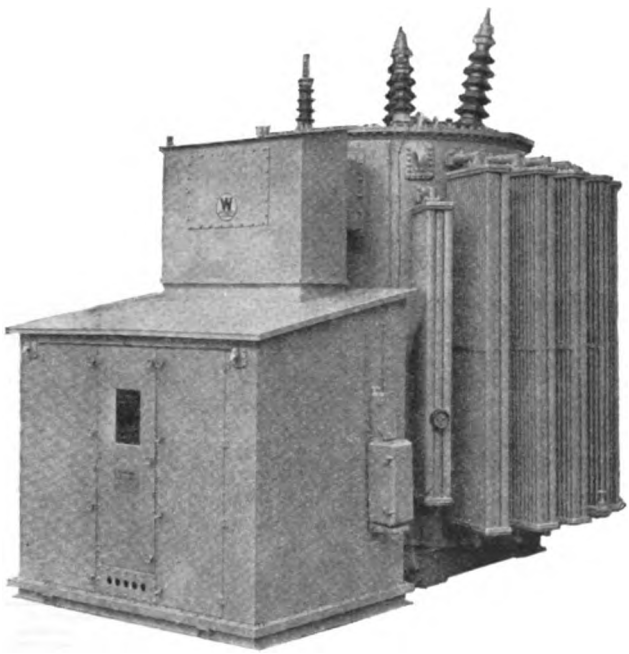

FIG. 1—A TRANSFORMER EQUIPPED WITH TAP-CHANGING MECHANISM

The single winding method shown in Fig. 5 is used. The transformer is rated at 10 500 kv-a, single-phase, 25 cycles, 60 000 to 13 100 volts.

If it is desired to interconnect the two systems through an additional line, which may be longer and probably of higher impedance, the total power transferred from one system to the other will depend upon the respective governor settings as before, but the kv-a and kw transferred will divide between the two lines in such a way that the voltage drop is the same over each line. If the lines have the same ratio of resistance to reactance, and charging capacity is neglected, both the kw and the kv-a will divide between the lines in inverse proportion to their impedances, provided the voltages on the two lines are respectively equal in phase and magnitude at both the sending and receiving ends. Since the two lines are of different impedances, the one of lower impedance will carry more than its share of the total, and may become seriously overloaded. If the lines have different ratios between resistance and reactance, or if the effect of capacitance is considered, the division will not be just the same, but the general result will be; in other words, one line may be overloaded.

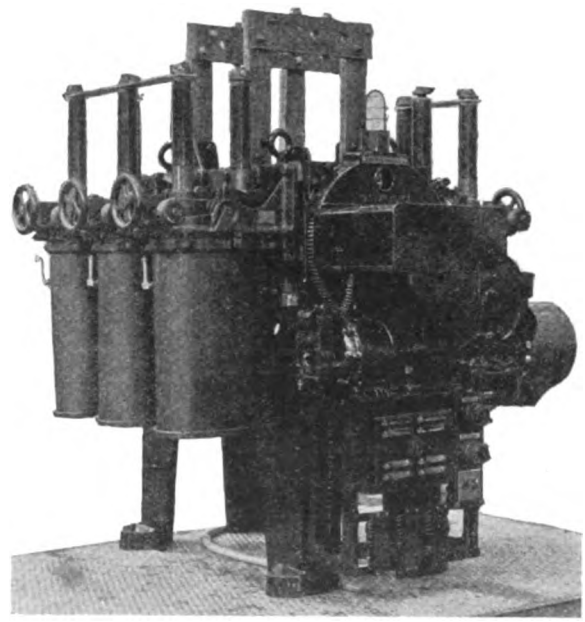

FIG. 2—THE TAP-CHANGING MECHANISM USED WITH THE TRANSFORMER OF FIG. 1

In general, the division of reactive kv-a between the two lines may be controlled by introducing an in-phase voltage into one or both lines by the use of equipment which changes the transformer ratio. Likewise, the division of kw load may be affected by introducing into one or both lines, equipment which changes the phase angle to compensate for the normal difference in phase angle, which would otherwise exist between the two lines for the required load division. This can be more readily understood by reference to a vector diagram.

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In Fig. 3, $E_B$ represents the voltage at one load center $B$ and $IR_c$ and $IX_c$ represent the ohmic and reactive drop in the first line $c$ from a point $A$. The sum of these items gives the voltage $E_{Ac}$ required at $A$ for the given load in line $c$. The second line $d$, by assumption is to carry the same load but over a greater distance, so that the $IR$ and $IX$ drops are greater. The resultant voltage $E_{Ad}$ required at $A$ is greater in magnitude and displaced in phase from voltage $E_{Ac}$.

If the lines are to carry equal kw and kv-a when connected together, either the impedance of line $c$ must be increased to that of line d, or a voltage $E_C$, equal to the difference between the two voltages, must be superimposed upon the circuit. Since the voltages are not in phase, simple voltage control is not sufficient, but adjustable phase-angle control is required in addition. This simple illustration indicates the great possibility of variable phase displacements occurring in intricate circuits which, if not corrected, may become objectionable on account of excessive circulating currents.

Fundamentally, phase-angle control is obtained by adding an adjustable voltage at an angle with the reference voltage. Referring to Fig. 4, $E_R$ represents vectorially the reference voltage and $E_\theta$ the voltage which is to be added in quadrature to the reference voltage. The angle $\theta$ represents the angle of phase displacement and can obviously be changed at will by changing the voltage $E_\theta$. Voltage control in the circuit is obtained by changing $E_r$. Phase-angle control, therefore, consists in changing taps under load in suitably connected windings.[1]

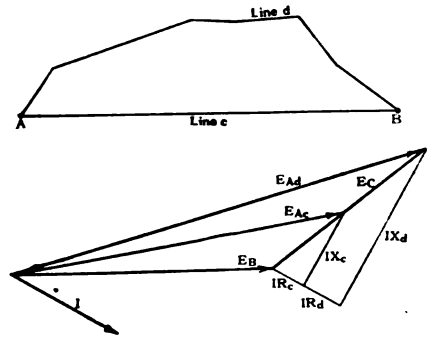


FIG. 3—VECTOR DIAGRAM ILLUSTRATING NEED FOR PHASE-ANGLE CONTROL EQUIPMENT

TYPICAL EQUIPMENT FOR CHANGING TAPS UNDER LOAD

The equipment now available for changing taps on transformers under load to obtain voltage control under load is adaptable to changing phase-angle under load. The simplest known method of transformer voltage control under load uses a single-winding in the transformer with a self-protecting autotransformer provided with a mid-tap[2]. Fig. 5 indicates the arrangement of the winding and the sequence of switch operation.

To obtain the entire transformer winding in the circuits, switch 1 is closed and the current passes through the transformer winding and the one-half of the preventive autotransformer. This gives a small impedance drop through the autotransformer, which is in series with the transformer. Since the drop is almost entirely reactive, the effect on regulation is practically negligible at ordinary power-factors.

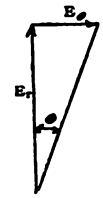


FIG. 4—VECTOR DIAGRAM ILLUSTRATING THE FUNDAMENTAL ACTION OF PHASE-ANGLE CONTROL EQUIPMENT

To change taps one step, switch 2 is closed, which places the autotransformer across the two taps, giving a voltage on the mid-tap of the autotransformer midway between the two actual tap voltages. To change taps another step, switch 1 is opened and the conditions become as before, with the other half of the autotransformer carrying the full current of the transformer. To change taps still further, the process is continued in the same manner, as may be followed in detail from the sequence chart, Fig. 5.

When full-load current is passed through one-half of the autotransformer with the other half open, the full-load current of the main transformer becomes the exciting current of the autotransformer. Under this condition, there are no neutralizing ampere turns from the other half, so the transformer becomes a reactor. Air-gaps are provided in the core to prevent saturation and give low impedance when operating in this manner, which of course, makes the exciting current, when operating as an autotransformer across taps, higher than ordinary.

A large transformer provided with this single-winding method of tap changing is shown in Fig. 1. The simple mechanical arrangement possible with this method is of great importance. The circuit breakers are operated mechanically, and may be seen with the motor-driven operating mechanism in Fig. 2. Typical control apparatus on the switchboard consists of a position indicator for each unit, indicating lamps, and a control switch for each bank.

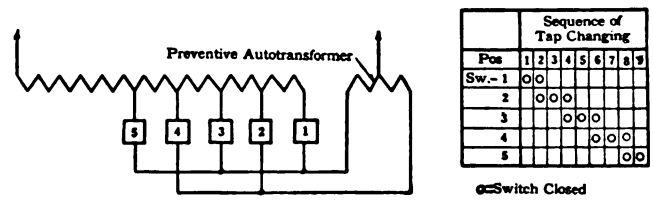


FIG. 5—SINGLE-WINDING METHOD OF VOLTAGE-CONTROL UNDER LOAD AND SEQUENCE OF SWITCH OPERATIONS

The operation of the control switch, either to raise or to lower the voltage, operates simultaneously the respective raise or lower motor switches on each of the tap changing mechanisms in a bank. As soon as the tap changing equipment starts to move, mechanically

[1] Phase-Angle Control may also be obtained in some applications by the use of two three-phase induction regulators. See "Transformer Tap Changing Under Load" by L. H. Hill, A.I.E.E. Journal, Nov. 1927.

[2] See "Changing Transformer Voltage" by K. A. Oplinger, Power, July 26, 1927.

"Transformer Tap Changing Under Load" by L. H. Hill, A.I.E.E. Journal, Nov. 1927.

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operated control switches close on the mechanism and complete the circuit until a tap-changing operation has been completed, regardless of further action of the operator.

The process of controlling phase angle under load

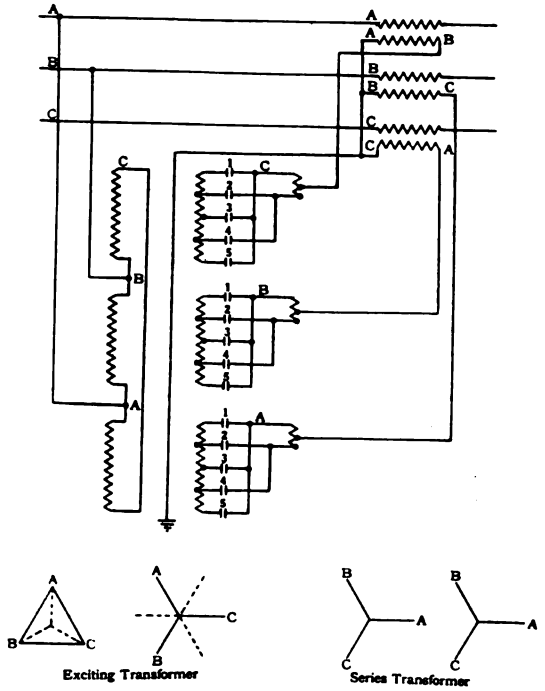


FIG. 6—A SEPARATE REGULATOR UNIT FOR PHASE-ANGLE CONTROL

consists in combining suitable variable quadrature components of voltages with the normal line voltages. With the system applications considered up to the present time, it appears that approximately plus or minus six degrees of phase control changed under load in

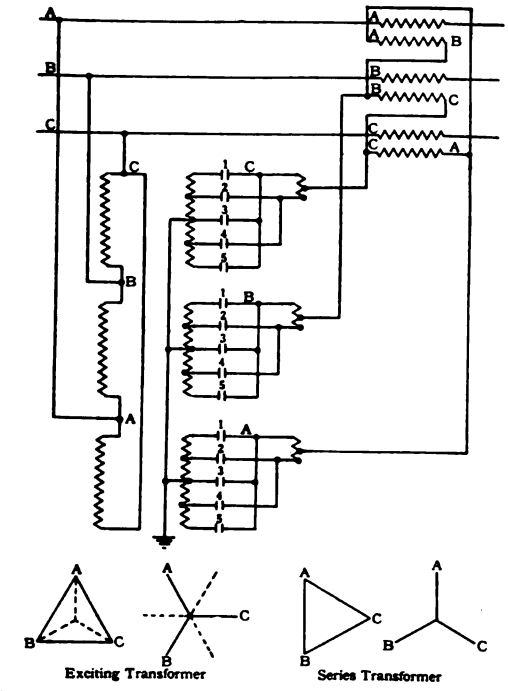


FIG. 7—A SEPARATE REGULATOR UNIT FOR VOLTAGE CONTROL

eight 1.5 percent steps will be satisfactory. Plus or minus six degrees phase control corresponds to about ten percent plus or minus quadrature voltage, which is a common range of application for tap-changing equipment used for voltage control under load. Equipment already developed for voltage control, therefore, applies equally well for phase-angle control.

While the fundamental principle employed for obtaining phase-angle control is the same for all applica-

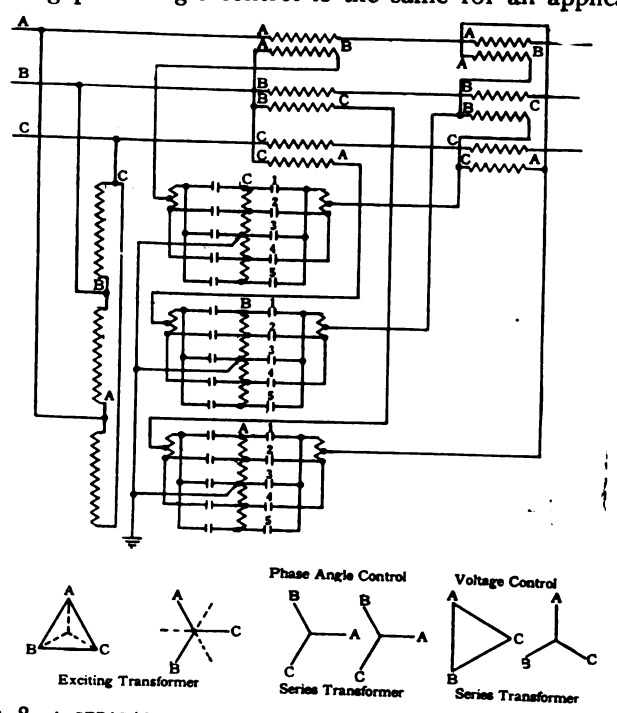


FIG. 8—A SEPARATE REGULATOR UNIT FOR COMBINED VOLTAGE AND PHASE-ANGLE CONTROL

tions, the particular circuit arrangement used depends on a number of factors, such as the line voltage, use of a solidly grounded neutral, phase displacement between the parts to be interconnected, etc.

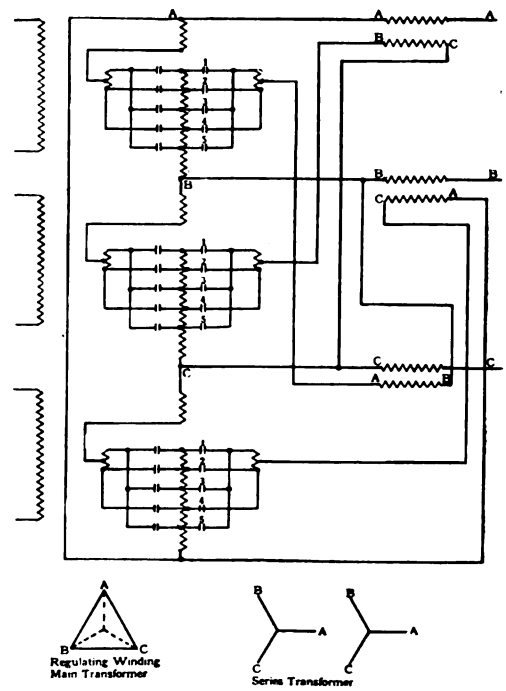


FIG. 9—APPLICATION OF COMBINED VOLTAGE AND PHASE-ANGLE CONTROL TO DELTA-CONNECTED MAIN TRANSFORMER

## SEPARATE PHASE-ANGLE REGULATING UNIT

At present a number of operating companies are making provision for the future installation of phase-

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angle control equipment, with immediate use of the voltage-control equipment. In this case the use of a separate regulating unit for phase-angle control which may be inserted in the line at any time is probably the most practical solution of the problem.

The connection of a three-phase unit for this purpose is illustrated schematically in Fig. 6. The primary of the exciting transformer is shown connected in delta, and the object is to obtain voltage in the secondary of the series transformer which will be at right angles to the normal line to neutral voltages indicated. The secondary of the exciting transformer is connected in star, and connections are made between it and the primary of the series transformer, which is connected in star to give a voltage in the secondary of the series transformer in quadrature with the normal line to neutral

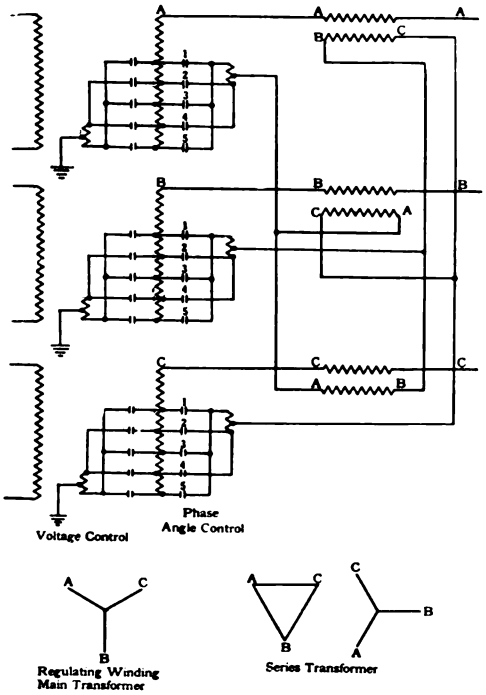


FIG. 10—APPLICATION OF COMBINED VOLTAGE AND PHASE-ANGLE CONTROL TO STAR-CONNECTED MAIN TRANSFORMER

voltage. The circuits are arranged to give equal amounts of positive or negative phase-angle control. For example, with the switches numbered 1 closed, the maximum phase displacement in one direction is obtained. If the switches numbered 3 are closed, zero displacement is obtained, and similarly, if the switches numbered 5 are closed, the maximum displacement in the opposite direction is obtained. The actual transitions between positions are made, of course, as indicated in the sequence diagram, Fig. 5.

Assuming a plus or minus six degrees of phase-angle control, the kv-a parts of the exciting transformer are about ten percent of the kv-a handled by the line, for the primary winding, and 20 percent for the secondary. The series transformer parts are each of the order of ten percent of the line capacity.

To show the simple relation between voltage control and phase-angle control, the similar circuit arrangement for a separate regulating unit for voltage control is shown in Fig. 7. The only change is to connect the primary of the series transformer in delta instead of in star. This gives voltages in the secondary of the series transformer in phase with the line to neutral voltages, which is the condition required for voltage control.

### SEPARATE COMBINED VOLTAGE AND PHASE-ANGLE REGULATING UNIT

In some cases it may be desired to provide both voltage and phase-angle control in a single, separate regulating unit. In this case the same exciting windings may be used and another tap-changing equipment used to apply adjustable voltage to another series transformer, as shown in Fig. 8. The connections between the regulating winding and the respective series transformers are identical with Figs. 6 and 7 respectively.

### APPLICATION OF COMBINED VOLTAGE AND PHASE-ANGLE CONTROL TO THE MAIN TRANSFORMERS

When combination voltage and phase-angle control is needed with new transformers, the control may usually be obtained directly on the main power transformers more economically than through the use of separate regulating units. Fig. 9 illustrates schematically the arrangement used when the winding in which the control is placed is delta connected, and Fig. 10 the arrangement when the winding is star connected.

## A High Temperature Motor

FIFTY-FIVE degrees C rise, plus 90 degrees C ambient, adds to 145 degrees C, or about 290 degrees F., a most unusual operating temperature for a motor. However, such a motor has been built. It is a 10 horse-power, 230-volt direct-current motor and will operate on the top of a steam boiler as a drive for stokers. This unusual motor application is the result of the extremely crowded condition of the particular power house.

The motor is not allowed to fan itself in the usual open-motor fashion, as the dust laden air around it would soon allow dirt to collect in the windings and short-circuit the commutator. The motor is entirely enclosed and is, therefore, of considerable size for its power output.

Paper, cotton, silk or any of the commonly used Class *A* insulating materials are, of course, entirely out of the question for such a motor. Some few bits of cotton string were used to tie the coils together and hold them in place until the motor was built. It is expected, however, that they will entirely carbonize in a short time after the motor goes into service. For insulation, then, only mica and asbestos were eligible. The mica is the usual built-up type. The binder, too, in this case will carbonize, but as its only function is to supply mechanical strength until the mica tape is in place this is unimportant. The gum commonly used in the field coils was replaced by varnish. Gum would start to ooze from the coil long before the operating temperatures were reached.

The motor is equipped with standard ball bearings, though a special, high-flash point of lubricant is necessary. At normal temperatures the lubricant is a thick heavy grease; at the motor operating temperatures it is a thin grease.

Although this is an unusual temperature for a motor it is not the maximum one possible. Motors can, and doubtless will be built for considerable higher temperatures when the occasion demands. The limiting temperature now seems to be the melting point of special, high-melting point solder which is, of course, in excess of 290 degrees F.

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# Dielectric Losses in Oil Impregnated Paper

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This paper presents the results of tests that were made on static condensers with the purpose of gathering more information on the subject of dielectric losses in oil impregnated paper. The variations of power-factor with voltage, frequency, and temperature are investigated, as well as the influence of the nature of the paper and of the impregnating medium. An attempt is made to explain the results found by the composite structure of the material and the possible influence of the well-known irreversible absorption current observed in liquid dielectrics.

ALTHOUGH much work has already been done on the subject of dielectric theory, a thorough understanding of the observed phenomena has not yet been reached, and the field of investigation remains widely unexplored. This is due to the number of different phenomena through which the nature of a dielectric reveals itself to the experimenter, and the number of variables that affect the phenomena. Among these are absorption, residual charge, alternating-current loss, insulation conductivity, all of which have the same or similar underlying causes, and dielectric breakdown that can often be traced back to the same origin. Each of these phenomena depends greatly on the conditions under which the tests are made, and on the nature and the state of the samples tested. It is not surprising therefore, that the data obtained on

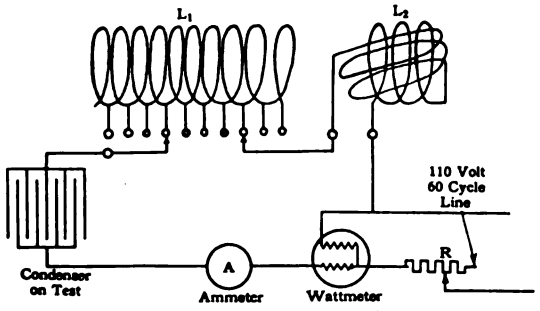


FIG. 1—ARRANGEMENT FOR MEASURING 60 CYCLES DIELECTRIC POWER-FACTOR

dielectrics is somewhat confusing and that great difficulties have been encountered in drawing conclusions therefrom.

This discussion outlines investigations in a small region of the field of dielectric phenomena, namely alternating-current losses in oil-impregnated paper. These investigations are not yet complete, but the results obtained give some interesting indications on various disputed points.

The samples used for the tests were commercial static condensers having oil impregnated paper for dielectric. Each sample thus consisted of a considerable mass of material completely enclosed in a metal box, so that no undesirable changes due to external influences could take place.

## POWER-FACTOR MEASUREMENTS

For the measurement of 60-cycle power-factor, the equipment indicated in Fig. 1 was used. The condenser to be tested is put in series with an inductance having sufficient taps to provide resonant conditions for condensers of widely different capacities. The variometer $L_2$ can be adjusted so that the whole circuit has about unity power-factor.

The current is adjusted by means of a rheostat so that the condenser can be tested at different voltages. The loss is measured by means of an ordinary wattmeter. The inductance was calibrated by means of a pyro-electric wattmeter, so that the inductance losses are known for the current used. These losses are added to those in the meters and the sum subtracted from the losses read on the wattmeter, the remainder being the loss in the condenser. The voltage across the condenser is determined either by a voltmeter or by computation from the values of the current and of the capacity of the condenser, as previously measured by a 60 cycle microfarad meter. The fact that the losses in the inductance were not more than double

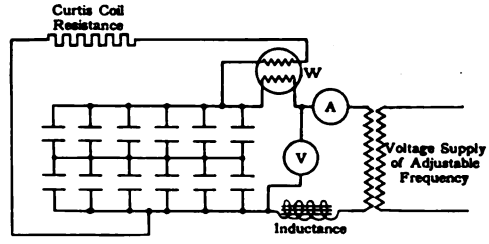


FIG. 2—ARRANGEMENT FOR MEASURING POWER-FACTOR AT LOW FREQUENCIES

the losses in the condenser made it possible to determine the latter with an error not greater than three percent.

When the voltage is determined by computation from the values of the current and the capacity, a slight error is made, by assuming that the condenser is a perfect capacity. This error usually has no appreciable influence on the evaluation of the power-factor, or can easily be taken into account.

For the measurements of power-factor at the lower frequencies, the equipment shown in Fig. 2 was used. To make tests at very low voltage stresses with sufficient accuracy, it was found necessary to put a great mass of insulation under test; two banks of six condensers in parallel were connected in series and the whole was considered as a sample of oil impregnated paper under test. The voltage was supplied by a generator driven by a direct-current motor whose speed could be easily adjusted to give different frequencies. In order to be sure that the wave form of the voltage applied to the condensers was free from harmonics,

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enough inductance was used to keep the circuit nearly in resonance.

The wattmeter used was a double dynamometer suspension type instrument fitted with removable coils. Special coils were made to measure the losses at low voltages and frequencies. The current and voltage

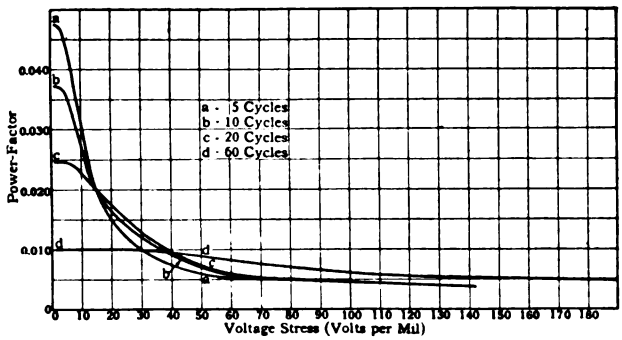


FIG. 3—VARIATION OF POWER-FACTOR WITH VOLTAGE

were measured by ordinary ammeters or voltmeters, or by thermocouple or dynamometer type instruments. In all cases, the necessary corrections were made.

## EXPERIMENTAL OBSERVATIONS

*Variations of Power-Factor with Voltage and Frequency*—The 12 condensers that constituted the sample under test were connected as shown in Fig. 2, and had a capacity of about 2.8 m.f.d. each. Their dielectric consisted of 10 sheets, each 0.00115 in. thick of a 70 percent cotton, 30 percent wood pulp paper. They had been thoroughly vacuum dried at 125 degrees C. and then impregnated under vacuum with transformer

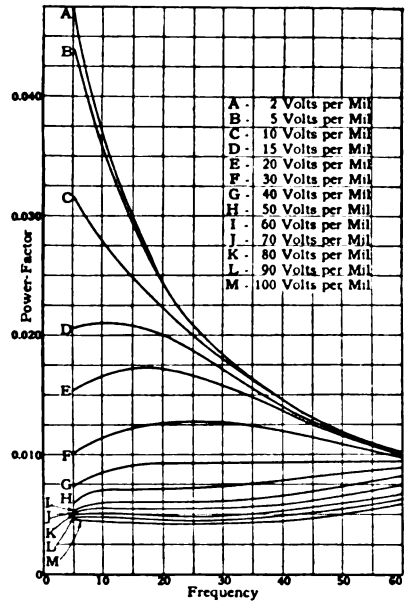
A - 2 Volts per Mil
B - 5 Volts per Mil
C - 10 Volts per Mil
D - 15 Volts per Mil
E - 20 Volts per Mil
F - 30 Volts per Mil
G - 40 Volts per Mil
H - 50 Volts per Mil
I - 60 Volts per Mil
J - 70 Volts per Mil
K - 80 Volts per Mil
L - 90 Volts per Mil
M - 100 Volts per Mil
Power-Factor
Frequency

FIG. 4—VARIATION OF POWER-FACTOR WITH FREQUENCY

oil. The results of the tests are given in Fig. 3, and another picture of the results of the same tests is shown in Fig. 4.

The decrease of power-factor with increased voltage, and the fact that this effect is more pronounced the lower the frequency, is very remarkable. The tests were made at room temperature. Many tests were made on a great number of condensers to determine the variations of 60 cycle power-factor with voltage. They all gave curves having the same general form as curve *d* of Fig. 3, that is, the power-factor remained constant at the lower voltages stresses, decreased continuously between 30 and 100 volts per mil, and then became again constant at the higher voltage stresses. These tests showed also that the power-factor depends upon the voltage per unit thickness, and is independent of the thickness of the dielectric. In other words the power factor really depends on the voltage stress and not on the voltage itself.

*Variations of Power-Factor with Temperature*—The shape of the power-factor temperature curve for oil-impregnated paper is well known and has caused the curve to be called the V curve. In trying to find out how certain factors affect the V curve for 60 cycle power-factor, a number of tests were made over a temperature range between — 15 and + 100 degrees C. For the tests at the higher temperatures, the condensers were heated in an oven and tested while they were cooling very slowly so that the entire mass of the insulation was always approximately at the same temperature. The temperatures were taken in the impregnating oil of the condenser. For the tests at the lower temperatures, the condensers were put in a refrigerator and then allowed to come up slowly to room temperature.

*Influence of Impregnating Oil*—V curves are given in Fig. 5 for three condensers made with the same kind of paper, the same number of sheets, vacuum dried in the same manner, but impregnated with different oils. Curve *A* refers to a condenser impregnated

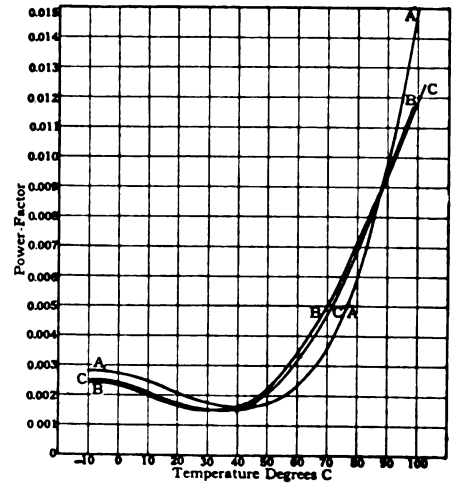


FIG. 5—THE INFLUENCE OF IMPREGNATING OILS ON THE V CURVE

with straight paraffin oil. For curves *B* and *C*, naphtene base oils containing different amounts of unsaturated hydrocarbons were used. The viscosity of oil *A* decreases with temperature more quickly than that of oils *B* and *C*. All three curves were made at the same voltage stress. The influence of the voltage stress over the shape of the V curve was not very pronounced, this being probably due to the fact that the tests were made in the region where the power-factor varies but little with the voltage.

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In order to determine more fully the influence of the impregnating medium, a condenser was thoroughly dried, and then impregnated with xylol. The results of the tests are shown in Fig. 6. The difference between this and oil impregnation is striking. Here the losses increase rapidly with temperature and the influence of the voltage stress is marked, the decrease of

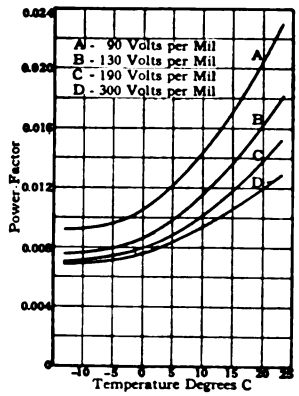


FIG. 6—VARIATION OF 60 CYCLES POWER-FACTOR WITH TEMPERATURE

power-factor with increasing voltage being more pronounced at the higher temperatures.

*Influence of Paper*—Tests on condensers made with two different kinds of paper showed that, even in the case where the losses were exactly the same at normal temperature, at high temperature the losses were higher for papers with a coarse structure, as shown in Fig. 7. Curve *A* corresponds to a cotton-wood pulp paper of quite coarse structure, and curve *B* to a linen paper of very fine structure. The drying treatment that had been applied to the condensers, and the impregnating oils, were the same in both cases.

*Influence of Residual Moisture*—With condensers

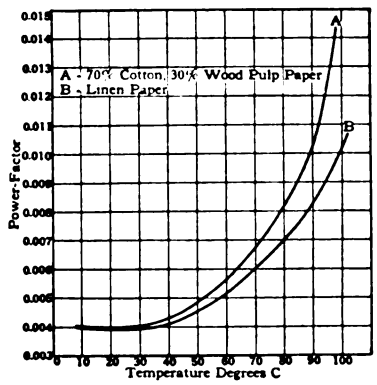


FIG. 7—INFLUENCE OF THE PAPER ON THE V CURVE

that had been dried to different extents the differences in power-factor were greater at normal than at high temperature. Fig. 8 illustrates this fact. Both condensers were identical as far as paper and impregnating oil were concerned. Only the drying process differed. Condenser *A* evidently was imperfectly dried and gave an appreciably higher power-factor than condenser *B*, that had been dried more thoroughly. However, the two V curves tend to draw together at high temperatures, indicating that the influence of residual moisture is then not predominant.

*Comparison of Power-Factor — Temperature Curves of a Condenser Before and After Impregnation*—Curve *A*, Fig. 9, was made on a condenser before it had been submitted to any drying treatment. Only the lower range of temperature could be investigated, as any heating might have evaporated the moisture inside of the condenser box. The condenser was then dried under vacuum at 75 degrees C. for 16 hours,

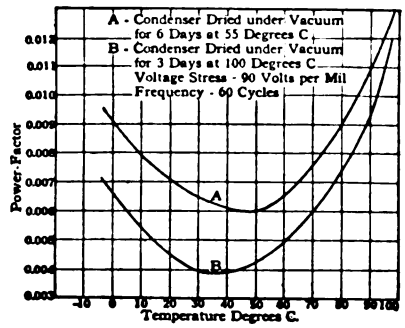
A - Condenser Dried under Vacuum for 6 Days at 55 Degrees C.
B - Condenser Dried under Vacuum for 3 Days at 100 Degrees C
Voltage Stress - 90 Volts per Mil
Frequency - 60 Cycles
Power-Factor
Temperature Degrees C.

FIG. 8—INFLUENCE OF RESIDUAL MOISTURE ON THE V CURVE

after which curve *B* was obtained, the condenser box being completely closed during the test so as to prevent any exchange of moisture with the atmosphere. The condenser was then submitted to a further vacuum drying at 125 degrees C. for 24 hours, and curve *C* was obtained, the same precautions being taken as before. Finally, the condenser being at normal temperature, it was again put under vacuum for a very short time to remove the air, and then impregnated with oil. The condenser thus completed was tested again and curve *D* was obtained. The relative positions of curves *C* and *D*, substantiated by repeated tests, are quite re-

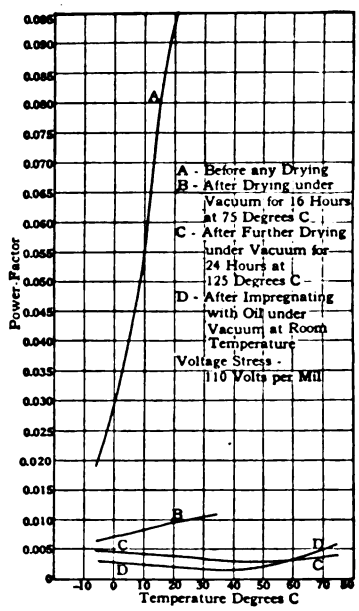
A - Before any Drying
B - After Drying under Vacuum for 16 Hours at 75 Degrees C.
C - After Further Drying under Vacuum for 24 Hours at 125 Degrees C
D - After Impregnating with Oil under Vacuum at Room Temperature
Voltage Stress - 110 Volts per Mil
Power-Factor
Temperature Degrees C

FIG. 9—INFLUENCE OF MOISTURE ON POWER-FACTOR TEMPERATURE CURVE

markable, as the quantity of residual moisture contained in the condenser was the same in both cases.

## THEORETICAL CONSIDERATIONS

A close examination of the experimental results suggests some interesting conclusions regarding the causes of dielectric losses and the part played in their

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formation by the different elements entering into the composition of the insulation.

The shape of the V curve has given rise to wide speculation. P. Dunsheath[1] has shown that the phenomenon could not be attributed to the ionization of entrapped gas bubbles, and has also clearly demonstrated that the view sometimes expressed that at the higher temperature the greater part of the dielectric loss can be attributed to conduction based on direct-current values is wrong. He suggests resolving the V curve into two components as shown in Fig. 10. It is then considered as the superposition of a curve $\alpha$ decreasing with temperature and of a curve $\beta$ increasing with it. He considers the dielectric as composed of capacities with resistances in series and in parallel, and explains curve $\alpha$ by the decrease of the series resistances and curve $\beta$ by the decrease of the shunting resistances. That such an effect really does take place is probable, but the explanation does not throw any light on the underlying causes of the dielectric loss. Let us retain, however, the idea of resolving the V curve into the two components, and see if these components are not due to different elements in the insulation.

If the curves of Fig. 8 are resolved into two components, the rising component $\beta$ will be the same for

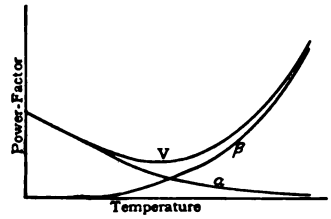


FIG. 10—THE V CURVE AND ITS COMPONENT

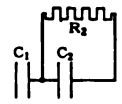


FIG. 11—REPRESENTATION OF A DIELECTRIC

the two curves, whereas the falling component $\alpha$ will be higher for curve $A$ than for curve $B$. This suggests immediately that the component $\alpha$ is due to the factor which is different in the two condensers, that is, to the amount of residual moisture in the paper, and that the component $\beta$ is due to the factor which is the same in both cases, that is, to the paper fibres and the impregnating oil.

If this interpretation is correct, the dielectric losses caused by the presence of residual moisture in the paper decrease with increasing temperature. The curves of Fig. 9 were made to investigate this point. But curve $A$ shows that the losses of unimpregnated and undried paper increase rapidly with temperature. After removal of the greater part of the moisture, curve $B$ shows that the losses still increase with temperature, but much less rapidly than before. Finally, curve $C$ shows that after a thorough drying, the loss actually decreases with temperature between 0 and + 40 degrees C., just as in the case of impregnated paper.

This last fact is a strong argument in favor of the theory that the component $\alpha$ of the V curve of impregnated paper represents the losses due to the residual moisture retained by the paper.

The mechanism of the variations of losses with temperature of unimpregnated paper containing residual moisture can be easily understood in the light of Maxwell's theory of imperfect dielectrics. Two distinct kinds of materials are present, one of low resistivity, the moisture, and the other comparatively infinite resistivity, the paper fibres and the air filling the interstices. It has become quite customary to illustrate Maxwell's theory by representing the dielectric by combinations of capacities and resistances. One of the simplest and most representative of these combinations is shown in Fig. 11, where capacity $C_1$ represents the infinite resistivity materials, and the leaky capacity $C_2$ the residual moisture.

The loss angle $\delta$ of such a model at a frequency is given by

$$tan\ \delta = \frac{\omega R_2 C_1}{1 + \omega^2 R_2^2 C_2 (C_1 + C_2)}$$

Let us see how the loss angle varies with the value of the resistance $R_2$, or better of the conductance $1/R_2$. The variations are shown in Fig. 12, the curve passing by a maximum for

$$1/R_2 = \omega \sqrt{C_2 (C_1 + C_2)}$$

Now at increased temperature, the resistance of the particles of moisture will decrease and, in the representative model, $R_2$ will decrease also. We may then consider $1/R_2$ as a continuously increasing function of

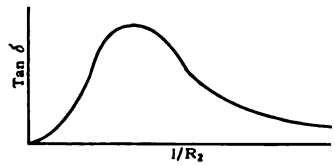


FIG. 12—VARIATION OF LOSS ANGLE WITH CONDUCTANCE

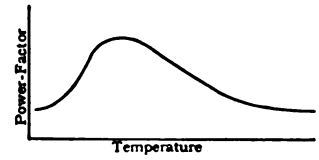


FIG 13—VARIATION OF LOSS ANGLE WITH TEMPERATURE

temperature. The loss angle of the model, as well as that of the real dielectric, will then vary with temperature in a manner shown approximately by Fig. 13, remembering that for these small angles, the loss angle its tangent and the power-factor are practically equal.

According to the preceding analysis, one would expect to find at low temperature a maximum for the power-factor of unimpregnated paper and also for the component $\alpha$ of the V curve of impregnated paper. Some experimenters have actually found such a maximum. Indications of such a maximum were found in our tests, as may be seen in Fig. 5. The curves of Fig. 9 also give some interesting indications along that line. Supposing for a moment that the power-factor—temperature curve of unimpregnated paper really has the shape shown in Fig. 13, what effect would a progressive removal of the moisture produce. As the moisture content diminishes, not only will the loss decrease and the curve become lower and lower, but also the resistance of the individual moisture particles will tend to decrease, owing to the increased concentration of their impurities following the evaporation. This last effect will cause the maximum of the curve to be shifted towards the lower temperatures, because at the given

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frequency, on account of their general lowering in resistance, the moisture particles will have the resistance value corresponding to the maximum loss at a temperature lower than previously. Therefore, one would expect the power-factor temperature curves of unimpregnated paper during moisture removal to undergo the changes indicated in Fig. 14.

It is now apparent that in Fig. 9 the experimental curves *A* and *B*, as well as the low temperature portion of curve *C*, might well be sections corresponding to a rather narrow range of temperatures, of curves that have the same general shape as those of Fig. 14.

Curve *C* of Fig. 9 shows that the power-factor of thoroughly dried, unimpregnated paper, after first decreasing with temperature, starts to increase at the higher temperatures. This is probably due to an effect of the temperature on the paper fibres themselves that causes a decrease in resistivity of some component elements.

Curve *D* of Fig. 9 indicates that, at the lower temperatures, the dielectric loss is less after impregnation than before. The result of the impregnation is to replace the air present in the paper by oil. At the low voltages, where no ionization could take place, the air acts as a perfect dielectric and can not be the seat of any loss. Yet, by replacing this perfect dielectric by another not so nearly perfect, the loss diminishes. The reason is apparent when one considers the behavior of the lines of force in a dielectric containing materials of different specific inductive capacities. In unimpregnated paper, there are three main kinds of materials, the paper fibres, the residual moisture, and the air, with dielectric constants of 4, 86, and 1 respectively. The residual moisture is in the form of small particles or thin films covering the surfaces of the paper fibres. When a voltage is applied across the dielectric, the lines of force will have a tendency to crowd through the moisture particles on account of their high specific inductive capacity. Experience has shown that the losses in unimpregnated paper can be accounted for quantitatively by Maxwell's theory of imperfect dielectrics only by taking into consideration this concentration of the lines of force in the moisture particles—a concentration that is due to the refraction of the lines of force at the surfaces of separation of the moisture from the media of lower specific inductive capacity, and that would not take place if the moisture were disposed in thin layers parallel to the electrodes. This concentration of lines of force explains how even very small quantities of moisture can be the cause of quite an appreciable dielectric loss.

This concentration will be the more important the lower the specific inductive capacities of the media surrounding the moisture particles. Therefore when, in the paper, we replace the air of dielectric constant 1 by oil of dielectric constant 2.3, the concentration of the lines of force in the moisture particles will be less pronounced and the dielectric losses will decrease.

It has already been intimated that the rising portion of the V curve is due mainly to the impregnating oil or to the material of the paper fibres themselves. The fact that in Fig. 9, curve *D* appears to increase quicker than curve *C* at the higher temperatures suggests that the influence of the impregnating oil is predominant. Moreover, the curves of Fig. 5 show that the nature of the oil affects the shape of that rising portion. Also the facts observed in the case of the condenser impregnated with xylol confirms the opinion that the main cause of the component $\beta$ must be looked for in the impregnating medium. In the case of the paper impregnated with xylol the loss due to the liquid impregnating medium is very important, and in that case the decrease of power-factor with increased voltage stress is unusually pronounced. This fact suggests the idea that the decrease of power-factor with voltage stress observed in Fig. 3 for oil-impregnated paper at normal temperature is also due to the influence of the impregnating medium. Moreover, the often-observed fact that wax impregnated paper does not show any

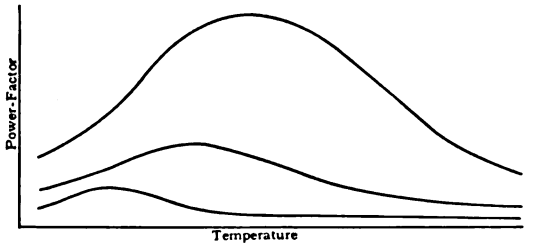


FIG. 14—EFFECT OF MOISTURE ON POWER-FACTOR TEMPERATURE CURVES OF UNIMPREGNATED PAPER

decrease in power-factor with voltage, and that the phenomenon occurs only in papers impregnated with liquids, is a further argument in favor of the theory. Let us therefore try to find an explanation for the results shown in Figs. 3 and 4 on the basis of the behavior of liquid dielectrics.

The phenomenon of the irreversible absorption current in liquid dielectrics is well known. This current flows only on charging and varies with time, decreasing until it reaches a final constant value. The time to reach this final constant value is decreased as the voltage is increased. This current can not be considered as a normal conduction current, since it does not obey Ohm's law. Its final value is not proportional to the voltage, but generally increases more slowly, and in some cases an apparent saturation current is observed. As Dr. Whitehead[2] expresses it: "With the continued application of electric force, the ions are swept to the electrodes and the current falls off; with a greater e.m.f., the ions are drained off more and more rapidly as compared with their rate of formation and so the conductivity falls off."

This phenomenon was also investigated by

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Tank,[3] who found that the anomalous current first remains constant for a very short time and then decreases until it reaches a final constant value; and that the decrease is quicker, the higher the constant voltage applied. Moreover, he appears to be of the opinion that the initial constant value of the current is proportional to the voltage. In Fig. 15 are shown the general curve shapes that would be expected according to Tank's observations when different constant voltages proportional to 1, 2, and 3, are applied.

Oil-impregnated paper contains a great number of minute masses of oil, separated by the materials of the fibers. When an e.m.f. is applied, it appears quite natural to say that anomalous currents will take place in every one of these minute masses of oil.

Let us try to figure out what anomalous currents would result in one of these minute masses of oil when an alternating e.m.f. is applied, and what would be the resulting energy losses. A complete mathematical analysis of the subject would encounter great difficulties, as in this case the memory function* depends on the actual value of the e.m.f. at every moment, and the principle of superposition can not be applied. We can, however, calculate the losses for a certain period of time during which a constant voltage is applied. This will give us an indication of what the losses would be for a half cycle of a sine wave of equal duration. If a constant voltage $E$ is applied for a time $t_1$ the current $i$ will vary with time according to one of the curves shown in Fig. 15, and during an interval of time $dt$ the energy loss will be $Eidt$. The total loss during the period of time $t_1$ will be

$$\left(W\right)_0^{t_1} = \int_0^{t_1} E\,i\,dt = E\int_0^{t_1} i\,dt$$

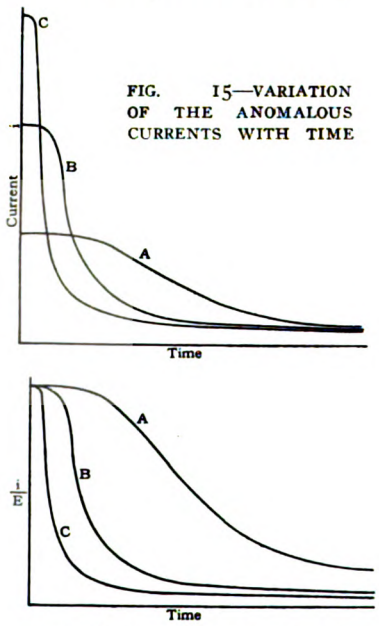


FIG. 15—VARIATION OF THE ANOMALOUS CURRENTS WITH TIME

FIG. 16—CURVES OF FIG. 15 REDUCED TO UNIT E.M.F.

The value of the integral will be given by the area limited by the curve, the ordinate of abscissa $t_1$ and the axis.

For convenience in the subsequent developments, let us reduce to unit e.m.f. the curves of Fig. 15. This has been done in Fig. 16, where the ratio $i/E$ is plotted against time for different values of $E$.

The total loss will then be given by

$$\left(W\right)_0^{t_1} = E^2\int_0^{t_1}\frac{i}{E}\,dt = E^2\left(w\right)_0^{t_1}$$

the integral being now the area limited by the new curve and representing the loss reduced to unit e.m.f. and designated by $\left(w\right)_0^{t_1}$ To obtain the variations of the loss with the duration of the application of the voltage, we need only to determine the variations of the area $\int_0^{t_1}\frac{i}{E}\,dt$ when $t_1$ increases.

This has been done graphically and the results are shown in Fig. 17, where the curves represent the variations of the loss reduced to unit e.m.f. with the duration of application of the constant voltage, for the three different values of that voltage.

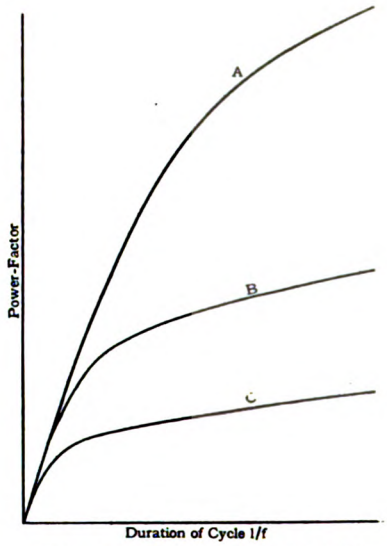


FIG. 17—VARIATION OF LOSS WITH DURATION OF CYCLE For voltages A, B, C proportional to 1, 2, 3.

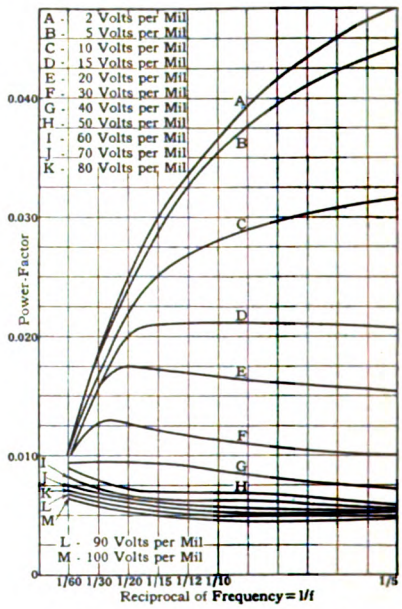
A - 2 Volts per Mil
B - 5 Volts per Mil
C - 10 Volts per Mil
D - 15 Volts per Mil
E - 20 Volts per Mil
F - 30 Volts per Mil
G - 40 Volts per Mil
H - 50 Volts per Mil
I - 60 Volts per Mil
J - 70 Volts per Mil
K - 80 Volts per Mil
L - 90 Volts per Mil
M - 100 Volts per Mil
Power-Factor
0.040
0.030
0.020
0.010
0
1/60 1/30 1/20 1/15 1/12 1/10 1/5
Reciprocal of Frequency = 1/f

FIG. 18—VARIATION OF POWER-FACTOR WITH DURATION OF CYCLE

The reason for the saturating shape of these curves is seen immediately. As long as the duration of application of the voltage does not exceed the short interval of time during which the anomalous current is constant, the loss increases proportionately with time. When the current begins to decrease, the loss increases more and more slowly. Now it is to be expected that the variations of the loss during a half cycle of a sine wave with the duration of that half cycle will be of the same nature as the variations of the loss under a constant voltage with the time of application of that voltage. Therefore, the curves of Fig. 17 ought approximately to represent the variations of the loss per cycle (reduced

*See "Lectures on Dielectric Theory and Insulation" by J. B. Whitehead, pp. 29-33 and 103-109.

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to unit e.m.f.) in the minute mass of oil submitted to an alternating stress, with the duration of the cycle.

According to Tank, the time interval during which the current is constant is much greater than the duration of a half cycle of any commercial frequency. This means that the loss per cycle would be proportional to the duration of the cycle, and that the curves of Fig. 17 would be practically straight lines with their saturating portion projected very far to the right. This would probably be the case for the loss per cycle—duration of cycle curves corresponding to masses of oil of the same order of magnitude as those on which Tank made his tests. But in oil-impregnated paper, we are concerned with extremely minute masses of oil for which in all probability, the whole phenomenon takes place much more rapidly, and where the current begins to fall off in a much shorter period of time.

It is probable, therefore, that for a minute mass of oil submitted to an alternating stress, the curves of the loss per cycle reduced to unit e.m.f. will have the form shown in Fig. 17. Now the duration of the cycle is the reciprocal of the frequency and the loss per cycle reduced to unit e.m.f. is nothing else but the dielectric power-factor multiplied by a constant depending on the capacity of the mass. We may, therefore, consider the curves of Fig. 17 as the probable curves of power-factor against the reciprocal of frequency.

Let us now examine the nature of the variations of power-factor with frequency for oil impregnated paper, where we have a great number of such minute masses of oil. From the results shown in Figs. 3 and 4 we deduce the curves of Fig. 18, representing the variations of power-factor with the reciprocal of frequency for different voltage stresses. We see immediately that the curves corresponding to the lower voltages have a striking resemblance to those of Fig. 17, a fact which indicates that probably the losses at the lower voltage stresses are due mainly to the anomalous currents in the impregnating oil. The curves of Fig. 18 corresponding to the higher voltage stresses have an entirely different aspect. This is due to the fact that under those conditions, the anomalous currents in the masses of oil fall off so rapidly that the losses they cause are negligible compared to the losses due to the residual moisture in the paper fibers, which then become predominant.

Let us consider again the influence of temperature. It is well known that the irreversible absorption current increases greatly with temperature. On this account, the power-factor that at room temperature and for the higher voltage stresses is hardly affected by the anomalous currents in the oil, starts to increase at the higher temperatures when the influence of these currents become predominant. Thus, the component $\beta$ of the V curve is due for the greater part to these currents in the oil.

If this is the case, the power-factor at high temperature should decrease with frequency. This must occur for any loss caused by the anomalous current in a liquid dielectric because, as we have seen, the loss per cycle always increases with the duration of that cycle.

This means that the component $\beta$ of the V curve is shifted towards the right as the frequency increases. On the other hand, the component $\alpha$ will also be shifted towards the right; that is its suggested maximum will be shifted towards the right, as the higher the frequency, the lower will be the moisture resistance giving the maximum and the greater the corresponding temperature. The whole V curve will then be shifted towards the higher temteratures when the frequency increases. In the discussion of Mr. P. Dunsheath's paper already referred to, Mr. Emanueli gave some power-factor temperature curves for different frequencies that show this very clearly.

It is true that Fig. 7 shows that the paper has a marked influence on the rising portion of the V curve. This may, however, be due not so much to an increase of the loss in the paper fibers as to the influence of the structure of the paper on the size of the masses of oil that are separated from one another by the fibers. It is difficult to decide on this point at present.

## SUMMARY AND CONCLUSIONS

From our investigations on the power-factor of oil impregnated paper at voltage stresses varying from 2 to 200 volts per mil and at frequencies varying from 5 to 60 cycles and on the variations of 60 cycle power-factor with temperature between —15 and +100 degrees C. we see that:

1—The power-factor at room temperature decreases with increasing voltage stresses.

2—At the low-voltage stresses, the power-factor is higher the lower the frequency, and the decrease in power-factor with voltage is more pronounced at the lower frequencies.

3—The variations of 60 cycle power-factor with temperature are represented by the well known V curve.

By analyzing the results obtained, we arrive at the following interpretations:

1—The V curve of power-factor against temperature may be considered as the superposition of two curves, one falling and representing the losses due to the presence of residual moisture in the paper fibers; and one rising, due partly to the influence of temperature on the paper, and partly to the increase of losses due to anomalous currents in the impregnating oil, the latter cause being most probably the predominant one.

2—The high values of power-factor at the lower frequencies and at the low-voltage stresses are due to the anomalous currents in the oil.

## REFERENCES

[1]P. Dunsheath—*I.E.E. Journal*, Vol. 64, No. 349 January 1926.

[2]J. B. Whitehead—*A.I.E.E. Journal*, June 1926.

[3]Tank. *Annalen der Physik*, 1915, Vol. 48, p. 307.

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# Symmetrical Components

## II--Resolution of Three Vector Products into Products of their Symmetrical Components

C. F. WAGNER and R. D. EVANS

The previous article discussed some of the fundamental theory of the method of symmetrical components, describing the method for the resolution of voltage or current vectors of a three phase system into their symmetrical components. The present article concludes the general discussion of the fundamental theory and is concerned chiefly with the resolution of voltage drops into their symmetrical components. This article developes the great simplification that obtains when the system is symmetrical at all points except the point at which a single phase load or fault is applied.

THE determination of voltage drops produced by currents flowing through unsymmetrical impedances will now be considered. Assume three impedances, $\check{Z}_a$, $\check{Z}_b$, and $\check{Z}_c$ connected in star to a neutral wire as shown in Fig. 10. Let currents $\check{I}_a$, $\check{I}_b$, and $\check{I}_c$ flow in the respective phases. Considering the individual phases the equations expressing the relations between currents and voltages are:

$$\check{E}_a = \check{Z}_a \check{I}_a \quad \ldots\ldots (54)$$
$$\check{E}_b = \check{Z}_b \check{I}_b \quad \ldots\ldots (55)$$
$$\check{E}_c = \check{Z}_c \check{I}_c \quad \ldots\ldots (56)$$

In general, the impedances $\check{Z}_a$, $\check{Z}_b$, $\check{Z}_c$ will be different in magnitude and power-factor. In general, also, the currents may be resolved into the three symmetrical components, the equations for which may be written as follows:—

$$\check{I}_a = \check{I}_{a1} + \check{I}_{a2} + \check{I}_{a0} \quad \ldots\ldots (57)$$
$$\check{I}_b = a^2 \check{I}_{a1} + a\check{I}_{a2} + \check{I}_{a0} \quad \ldots\ldots (58)$$
$$\check{I}_c = a \check{I}_{a1} + a^2 \check{I}_{a2} + \check{I}_{a0} \quad \ldots\ldots (59)$$

Substituting the value of currents from equations (57) to (59) in equations (54) to (56) gives:—

$$\check{E}_a = (\check{Z}_a) \check{I}_{a1} + (\check{Z}_a) \check{I}_{a2} + (\check{Z}_a) \check{I}_{a0} \quad \ldots\ldots (60)$$
$$\check{E}_b = (a^2 \check{Z}_b) \check{I}_{a1} + (a \check{Z}_b) \check{I}_{a2} + (\check{Z}_b) \check{I}_{a0} \quad \ldots\ldots (61)$$
$$\check{E}_c = (a \check{Z}_c) \check{I}_{a1} + (a^2 \check{Z}_c) \check{I}_{a2} + (\check{Z}_c) \check{I}_{a0} \quad \ldots\ldots (62)$$

As shown in the preceding article the voltages $\check{E}_a$, $\check{E}_b$, and $\check{E}_c$, may be resolved into their symmetrical components as follows:—

$$\check{E}_{a1} = 1/3\,(\check{E}_a + a\,\check{E}_b + a^2 \check{E}_c) \quad \ldots\ldots (63)$$
$$\check{E}_{a2} = 1/3\,(\check{E}_a + a^2 \check{E}_b + a\check{E}_c) \quad \ldots\ldots (64)$$
$$\check{E}_{a0} = 1/3\,(\check{E}_a + \check{E}_b + \check{E}_c) \quad \ldots\ldots (65)$$

The various symmetrical components of voltages may now be expressed in terms of impedance drops by substituting the values of $\check{E}_a$, $\check{E}_b$ and $\check{E}_c$, from equations (60) to (62) in equations (63) to (65) with the following results:—

$$\check{E}_{a1} = 1/3\,(\check{Z}_a + \check{Z}_b + \check{Z}_c)\,\check{I}_{a1} + 1/3\,(\check{Z}_a + a^2 \check{Z}_b + a\,\check{Z}_c)\,\check{I}_{a2} + 1/3\,(\check{Z}_a + a\check{Z}_b + a^2 \check{Z}_c)\,\check{I}_{a0} \quad \ldots\ldots (66)$$

$$\check{E}_{a2} = 1/3\,(\check{Z}_a + a\,\check{Z}_b + a^2 \check{Z}_c)\,\check{I}_{a1} + 1/3\,(\check{Z}_a + \check{Z}_b + \check{Z}_c)\,\check{I}_{a2} + 1/3\,(\check{Z}_a + a^2 \check{Z}_b + a\,\check{Z}_c)\,\check{I}_{a0} \quad \ldots\ldots (67)$$

$$\check{E}_{a0} = 1/3\,(\check{Z}_a + a^2\check{Z}_b + a\,\check{Z}_c)\,\check{I}_{a1} + 1/3\,(\check{Z}_a + a\,\check{Z}_b + a^2 \check{Z}_c)\,\check{I}_{a2} + 1/3\,(\check{Z}_a + \check{Z}_b + \check{Z}_c)\,\check{I}_{a0} \quad \ldots\ldots (68)$$

It will be observed that the voltage drop produced by the circulation of current through unsymmetrical impedances is made up of three impedance drops. Closer examination will show that while nine terms are involved there are only three distinct impedances:

$$1/3\,(\check{Z}_a + \check{Z}_b + \check{Z}_c),\quad 1/3\,(\check{Z}_a + a\,\check{Z}_b + a^2 \check{Z}_c),$$
$$1/3\,(\check{Z}_a + a^2 \check{Z}_b + a\,\check{Z}_c)$$

These terms are impedances since they are the ratio of the voltages impressed to the currents flowing. It will be noted that the voltage drops may be arranged to form three symmetrical terms forming a positive, a negative and a zero sequence system. Study of the voltage drops will show that the voltage drops of one symmetrical component are not always produced by currents of the corresponding symmetrical component. There is, moreover, a certain sequence which may be observed in the arrangement of terms producing the voltage drops. This makes possible an important simplification in the general theory of the method of symmetrical components. This is obtained by forming the voltage drops with the use of the sequence operator.

The relations which have been developed in the

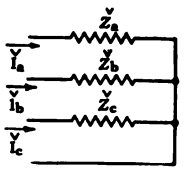


FIG. 10—STAR CONNECTED IMPEDANCES

preceding paragraphs can be stated more generally in the following theorem:—

*Theorem:—Any three vector products* $S(\check{K}_x \check{I}_a) =$
$\check{K}_x \check{I}_a, \check{K}_y \check{I}_b, \check{K}_z \check{I}_c = S^0 (\check{K}_0 \check{I}_0 + \check{K}_2 \check{I}_1 + \check{K}_1 \check{I}_2) + S^1 (\check{K}_1 \check{I}_0 + \check{K}_0 \check{I}_1 + \check{K}_2 \check{I}_2) + S^2 (\check{K}_2 \check{I}_0 + \check{K}_1 \check{I}_1 + \check{K}_0 \check{I}_2)$ ..... (69)

where

$$\left.\begin{aligned} \check{K}_0 &= 1/3\,(\check{K}_x + \check{K}_y + \check{K}_z) \\ \check{K}_1 &= 1/3\,(\check{K}_x + a\,\check{K}_y + a^2 \check{K}_z) \\ \check{K}_2 &= 1/3\,(\check{K}_x + a^2 \check{K}_y + a\,\check{K}_z) \\ \check{I}_0 &= 1/3\,(\check{I}_a + \check{I}_b + \check{I}_c) \\ \check{I}_1 &= 1/3\,(\check{I}_a + a\,\check{I}_b + a^2 \check{I}_c) \\ \check{I}_2 &= 1/3\,(\check{I}_a + a^2 \check{I}_b + a\,\check{I}_c) \end{aligned}\right\} \quad \ldots\ldots (70)$$

The proof of this relation may be demonstrated as follows: Substituting the values of the individual terms in the original products gives:—

$$\check{K}_x \check{I}_a = (\check{K}_0 + \check{K}_1 + \check{K}_2)\,(\check{I}_0 + \check{I}_1 + \check{I}_2)$$
$$\check{K}_y \check{I}_b = (\check{K}_0 + a^2 \check{K}_1 + a\,\check{K}_2)\,(\check{I}_0 + a^2 \check{I}_1 + a\,\check{I}_2)$$
$$\check{K}_z \check{I}_c = (\check{K}_0 + a\,\check{K}_1 + a^2 \check{K}_2)\,(\check{I}_0 + a\,\check{I}_1 + a^2 \check{I}_2)$$

Expanding these expressions and rearranging:—

$$\left.\begin{aligned} \check{K}_x \check{I}_a &= (\check{K}_0 \check{I}_0 + \check{K}_2 \check{I}_1 + \check{K}_1 \check{I}_2) + (\check{K}_1 \check{I}_0 + \check{K}_0 \check{I}_1 + \check{K}_2 \check{I}_2) + (\check{K}_2 \check{I}_0 + \check{K}_1 \check{I}_1 + \check{K}_0 \check{I}_2) \\ \check{K}_y \check{I}_b &= (\check{K}_0 \check{I}_0 + \check{K}_2 \check{I}_1 + \check{K}_1 \check{I}_2) + a^2 (\check{K}_1 \check{I}_0 + \check{K}_0 \check{I}_1 + \check{K}_2 \check{I}_2) + a(\check{K}_2 \check{I}_0 + \check{K}_1 \check{I}_1 + \check{K}_0 \check{I}_2) \\ \check{K}_z \check{I}_c &= (\check{K}_0 \check{I}_0 + \check{K}_2 \check{I}_1 + \check{K}_1 \check{I}_2) + a(\check{K}_1 \check{I}_0 + \check{K}_0 \check{I}_1 + \check{K}_2 \check{I}_2) + a^2 (\check{K}_2 \check{I}_0 + \check{K}_1 \check{I}_1 + \check{K}_0 \check{I}_2) \end{aligned}\right\} \quad \ldots\ldots (71)$$

which proves the above theorem.

An interesting fact concerning these expressions is

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that the first, second and third terms in parentheses in each equation are equal. In addition the coefficients of the first term form the zero sequence, those of the second term the positive sequence, and those of the third term the negative sequence. This suggests the following short cut notation to represent the relation:—

$$S(\check{K}_x \check{I}_a) = \left\{ \begin{matrix} \check{K}_x \check{I}_a \\ \check{K}_y \check{I}_b \\ \check{K}_z \check{I}_c \end{matrix} \right\} = S^0(\check{K}_0\check{I}_0 + \check{K}_2\check{I}_1 + \check{K}_1\check{I}_2) + S^1(\check{K}_1\check{I}_0 + \check{K}_0\check{I}_1 + \check{K}_2\check{I}_2) + S^2(\check{K}_2\check{I}_0 + \check{K}_1\check{I}_1 + \check{K}_0\check{I}_2) \quad \ldots\ldots (72)$$

Using the laws developed for the sequence operators these same results can be obtained by a much more elegant method:—

$$\begin{aligned} &\check{K}_x\check{I}_a, \check{K}_y\check{I}_b, \check{K}_z\check{I}_c = S(\check{K}_x\check{I}_a) \\ &= S(\check{K}_x)\ S(\check{I}_a) \\ &= [S^0(\check{K}_0) + S^1(\check{K}_1) + S^2(\check{K}_2)]\ [S^0(\check{I}_0) + S^1(\check{I}_1) + S^2(\check{I}_2)] \\ &= S^0(\check{K}_0)\ S^0(\check{I}_0) + S^0(\check{K}_0)\ S^1(\check{I}_1) + S^0(\check{K}_0)\ S^2(\check{I}_2) \\ &+ S^1(\check{K}_1)\ S^0(\check{I}_0) + S^1(\check{K}_1)\ S^1(\check{I}_1) + S^1(\check{K}_1)\ S^2(\check{I}_2) \\ &+ S^2(\check{K}_2)\ S^0(\check{I}_0) + S^2(\check{K}_2)\ S^1(\check{I}_1) + S^2(\check{K}_2)\ S^2(\check{I}_2) \end{aligned}$$

Recalling the laws of exponents as applying to the sequence operators:—

$$\begin{aligned} &= S^0[\check{K}_0\check{I}_0 + \check{K}_1\check{I}_2 + \check{K}_2\check{I}_1] \\ &+ S^1[\check{K}_0\check{I}_1 + \check{K}_1\check{I}_0 + \check{K}_2\check{I}_2] \\ &+ S^2[\check{K}_0\check{I}_2 + \check{K}_1\check{I}_1 + \check{K}_2\check{I}_0] \end{aligned}$$

Inasmuch as the value of the subscript always corresponds to the sequence, the same law also applies to them. The zero sequence component of the products is comprised of all those terms whose subscripts can add to zero (or multiples of 3), the positive sequence components of those terms which can add to unity (or 4), and the negative sequence of those which can add to 2 (or 5).

What of the physical significance of these expressions? This will be made clear by applying the deductions to the case first considered, viz., an impedance $\check{Z}_a$ in phase *a*, $\check{Z}_b$ in phase *b*, and $\check{Z}_c$ in phase *c*. The question arises "What are the voltage drops in terms of the symmetrical components of the impedances and currents?" The actual drops may be written

$$S(\check{Z}_a\check{I}_a) = \left\{ \begin{matrix} \check{Z}_a \check{I}_a \\ \check{Z}_b \check{I}_b \\ \check{Z}_c \check{I}_c \end{matrix} \right\} = + S^0(\check{Z}_0\check{I}_0 + \check{Z}_2\check{I}_1 + \check{Z}_1\check{I}_2) + S^1(\check{Z}_1\check{I}_0 + \check{Z}_0\check{I}_1 + \check{Z}_2\check{I}_2) + S^2(\check{Z}_2\check{I}_0 + \check{Z}_1\check{I}_1 + \check{Z}_0\check{I}_2) \quad \ldots\ldots (73)$$

Consider the case in which the three impedances are equal. It is evident for this case that if only currents of zero phase sequence flow, only voltage drops of zero sequence are present. This result may be checked mathematically. When the impedances are equal, $\check{Z}_1$ and $\check{Z}_2$ are equal to zero and since $\check{I}_1$ and $\check{I}_2$ are zero all the terms but $S^0$ $(\check{Z}_0\check{I}_0)$ disappear. If only positive sequence currents are present all terms but $S^1$ $(\check{Z}_0\check{I}_1)$ disappear and similarly, if only negative sequence currents are present all terms but $S^2$ $(\check{Z}_0\check{I}_2)$ disappear.

Consider next the case in which the impedances in the three phases form a positive phase sequence.

$$\left. \begin{aligned} \check{Z}_a &= \check{Z} \\ \check{Z}_b &= a^2\check{Z} \\ \check{Z}_c &= a\check{Z} \end{aligned} \right\} \quad \ldots\ldots (74)$$

This requires in the impedances both positive and negative reactances and resistances. Negative reactance may be represented by condensers, but how may negative resistances be obtained? Negative resistance characteristics may be obtained by vacuum tube set-ups or by series commutator machines in the leads. Of course, this assumption is only hypothetical. It is merely introduced to clear up the conceptions of unbalanced impedances. In this case

$$\left. \begin{aligned} \check{Z}_0 &= 1/3\,[\check{Z} + a^2\check{Z} + a\check{Z}] = 0 \\ \check{Z}_1 &= 1/3\,[\check{Z} + a(a^2\check{Z}) + a^2(a\check{Z})] = \check{Z} \\ \check{Z}_2 &= 1/3\,[\check{Z} + a^2(a^2\check{Z}) + a(a\check{Z})] = 0 \end{aligned} \right\} \quad \ldots\ldots (75)$$

Again assume that only zero sequence currents flow, the drops in this case are $\check{Z}\check{I}_0$, $a^2\check{Z}\check{I}_0$, and $a\check{Z}\check{I}_0$. It can be seen that these drops form a positive phase sequence; a zero phase sequence current passing through positive phase sequence impedances produces positive phase sequence voltage drops. This conclusion can be verified mathematically by inserting the values of $\check{Z}_0$, $\check{Z}_1$, and $\check{Z}_2$ from equations (75) in equation (73). When only zero sequence currents are present all of the terms except $S^1$ $(\check{Z}_1\check{I}_0)$ vanish. With only positive sequence current present the drops

$$\begin{aligned} \check{Z}_a\check{I}_a, \check{Z}_b\check{I}_b, \check{Z}_c\check{I}_c &= \check{Z}\check{I}, a^2\check{Z}\cdot a^2\check{I}, a\check{Z}\cdot a\check{I} \\ &= \check{Z}\check{I}, a\check{Z}\check{I}, a^2\check{Z}\check{I} \end{aligned}$$

are obtained. These drops it will be noted are of negative sequence. Again referring to equation (73) this result will be confirmed as all drops but the $\check{Z}_1\check{I}_1$ of the negative sequence vanish.

Similar conceptions may be shown for impedances of negative sequence.

Now comparing the expression for the voltage drops $S$ $(\check{Z}_a\check{I}_a)$ with the expression for the voltage drop in a single phase circuit $\check{Z}\check{I}$, the advantage of the notation by the sequence operators becomes apparent. It enables one to express the same relations for a polyphase system as the simple quantity $\check{Z}\check{I}$ expresses for the single-phase system. It simplifies the polyphase system to the same extent as the *j* operator simplified the single-phase alternating-current system.

## UNSYMMETRICAL NETWORK CONTAINING SELF AND MUTUAL IMPEDANCES

In very few polyphase circuits are the phases independent of each other; they are usually coupled electromagnetically. In transmission lines the mutual coupling is quite large, but it is usually cancelled out by the method of calculating the self inductance. Only that space field between the conductors is considered. This conveys the impression that the mutual inductance is nil. In polyphase machines such as generators, motors (synchronous and asynchronous), synchronous condensers and induction regulators, the coupling between phases is considerable. The exceptional cases in which the phases are not coupled are lighting and electric furnace loads. In the remainder of this article it will be shown that for circuits in which the impedances are symmetrical, even though they contain mutual inductances, the three phase sequences may be treated en-

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tirely independently; there is no interference between different sequences. This results in considerable simplification; and when it is recalled that with but few exceptions all of our circuits are symmetrical this result becomes extremely important. It will be shown that for such circuits the important constants are the impedances to positive sequence, negative sequence and zero sequence currents.

Those readers who are not particularly interested in the proofs for all the theorems, but are willing to accept the above statements on faith, might omit the remainder of this article with little loss of continuity.

Consider the circuit shown in Fig. 11. It is desired to express the drop across the impedances in terms of the symmetrical components of the current and self and mutual impedances. Let the current $\check{I}_a$, $\check{I}_b$, and $\check{I}_c$ flow in the three phases respectively, and let the self impedances be $\check{Z}_{aa}$, $\check{Z}_{bb}$, and $\check{Z}_{cc}$. In addition, let $\check{Z}_{ab}$ be the mutual impedance between phases $a$ and $b$, $\check{Z}_{bc}$ that between phases $b$ and $c$, and $\check{Z}_{ca}$ that between phases $c$ and $a$.

The drops involved may be arranged in three groups:

I—Potential drop in $a$ due to current in $a = \check{Z}_{aa}\check{I}_a$
Potential drop in $b$ due to current in $b = \check{Z}_{bb}\check{I}_b$
Potential drop in $c$ due to current in $c = \check{Z}_{cc}\check{I}_c$
II—Potential drop in $a$ due to current in $b = \check{Z}_{ab}\check{I}_b$
Potential drop in $b$ due to current in $c = \check{Z}_{bc}\check{I}_c$
Potential drop in $c$ due to current in $a = \check{Z}_{ca}\check{I}_a$
III—Potential drop in $a$ due to current in $c = \check{Z}_{ac}\check{I}_c$
Potential drop in $b$ due to current in $a = \check{Z}_{ba}\check{I}_a$
Potential drop in $c$ due to current in $b = \check{Z}_{cb}\check{I}_b$

The terms of group I represent the voltage drops due to the self impedances and is the same as that just treated. It consists of the three vector products

$$\check{Z}_{aa}\check{I}_a, \quad \check{Z}_{bb}\check{I}_b, \quad \check{Z}_{cc}\check{I}_c$$

Referring to the theorem relating to resolution of vector products into symmetrical form these drops may be expressed as follows:

$$\left.\begin{matrix}\check{Z}_{aa}\check{I}_a\\ \check{Z}_{bb}\check{I}_b\\ \check{Z}_{cc}\check{I}_c\end{matrix}\right\} = S(\check{Z}_{aa}\check{I}_a)$$

$$\left.\begin{matrix}= S^0(\check{Z}_{aa0}\check{I}_{a0} + \check{Z}_{aa2}\check{I}_{a1} + \check{Z}_{aa1}\check{I}_{a2})\\ + S^1\check{Z}_{aa1}\check{I}_{a0} + \check{Z}_{aa0}\check{I}_{a1} + \check{Z}_{aa2}\check{I}_{a2})\\ + S^2(\check{Z}_{aa2}\check{I}_{a0} + \check{Z}_{aa1}\check{I}_{a1} + \check{Z}_{aa0}\check{I}a^2)\end{matrix}\right\} \quad \text{.....(23)}$$

Where

$$\left.\begin{matrix}\check{Z}_{aa0} = 1/3(\check{Z}_{aa} + \check{Z}_{bb} + \check{Z}_{cc})\\ \check{Z}_{aa1} = 1/3(\check{Z}_{aa} + a\check{Z}_{bb} + a^2\check{Z}_{cc})\\ \check{Z}_{aa2} = 1/3(\check{Z}_{aa} + a^2\check{Z}_{bb} + a\check{Z}_{cc})\end{matrix}\right\} \quad \text{.....(24)}$$

Considering the terms of Group II, the voltages induced in the three phases $a$, $b$, and $c$ are respectively

$$\check{Z}_{ab}\check{I}_b, \quad \check{Z}_{bc}\check{I}_c, \quad \check{Z}_{ca}\check{I}_a$$

Again, using the three product theorem

$$\left.\begin{matrix}\check{Z}_{ab}\check{I}_b\\ \check{Z}_{bc}\check{I}_c\\ \check{Z}_{ca}\check{I}_a\end{matrix}\right\} = S(\check{Z}_{ab}\check{I}_b)$$

$$\left.\begin{matrix}= S^0(\check{Z}_{ab0}\check{I}_{b0} + \check{Z}_{ab2}\check{I}_{b1} + \check{Z}_{ab1}\check{I}_{b2})\\ + S^1(\check{Z}_{ab1}\check{I}_{b0} + \check{Z}_{ab0}\check{I}_{b1} + \check{Z}_{ab2}\check{I}_{b2})\\ + S^2(\check{Z}_{ab2}\check{I}_{b0} + \check{Z}_{ab1}\check{I}_{b1} + \check{Z}_{ab0}\check{I}_{b2})\end{matrix}\right\} \quad \text{.....(78)}$$

Where

$$\left.\begin{matrix}\check{Z}_{ab0} = 1/3(\check{Z}_{ab} + \check{Z}_{bc} + \check{Z}_{ca})\\ \check{Z}_{ab1} = 1/3(\check{Z}_{ab} + a\check{Z}_{bc} + a^2\check{Z}_{ca})\\ \check{Z}_{ab2} = 1/3(\check{Z}_{ab} + a^2\check{Z}_{bc} + a\check{Z}_{ca})\end{matrix}\right\} \quad \text{.....(79)}$$

In the above expressions the nomenclature $\check{I}_{b1}$ and $\check{I}_{b2}$ is used to indicate that the first term in the group, the reference or datum vector, has been changed to the $b$ phase. Now, since

$$\check{I}_{b0} = \check{I}_{a0}$$
$$\check{I}_{b1} = a^2\check{I}_{a1}$$
$$\check{I}_{b2} = a\check{I}_{a2}$$

$$S(\check{Z}_{ab}\check{I}_b) = S^0(\check{Z}_{ab0}\check{I}_{a0} + \check{Z}_{ab2}a^2\check{I}_{a1} + \check{Z}_{ab1}a\check{I}_{a2}) + S^1(\check{Z}_{ab1}\check{I}_{a0} + \check{Z}_{ab0}a^2\check{I}_{a1} + \check{Z}_{ab2}a\check{I}_{a2}) + S^2(\check{Z}_{ab2}\check{I}_{a0} + \check{Z}_{ab1}a^2\check{I}_{a1} + \check{Z}_{ab0}a\check{I}_{a2}) \quad \text{..(80)}$$

Considering the terms of group III in a similar manner:

$$\left.\begin{matrix}\check{Z}_{ac}\check{I}_c\\ \check{Z}_{ba}\check{I}_a\\ \check{Z}_{cb}\check{I}_b\end{matrix}\right\} = S(\check{Z}_{ac}\check{I}_c)$$

$$\left.\begin{matrix}= S^0(\check{Z}_{ac0}\check{I}_{c0} + \check{Z}_{ac2}\check{I}_{c1} + \check{Z}_{ac1}\check{I}_{c2})\\ + S^1(\check{Z}_{ac1}\check{I}_{c0} + \check{Z}_{ac0}\check{I}_{c1} + \check{Z}_{ac2}\check{I}_{c2})\\ + S^2(\check{Z}_{ac2}\check{I}_{c0} + \check{Z}_{ac1}\check{I}_{c1} + \check{Z}_{ac0}\check{I}_{c2})\end{matrix}\right\} \quad \text{.....(81)}$$

Since

$$\check{I}_{c0} = \check{I}_{a0} \qquad \check{Z}_{ac} = \check{Z}_{ac}$$
$$\check{I}_{c1} = a\check{I}_{a1} \qquad \check{Z}_{ba} = \check{Z}_{ab}$$
$$\check{I}_{c2} = a^2\check{I}_{a2} \qquad \check{Z}_{cb} = \check{Z}_{bc}$$

and

$$\left.\begin{matrix}\check{Z}_{ac0} = 1/3(\check{Z}_{ac} + \check{Z}_{ba} + \check{Z}_{cb}) = \check{Z}_{ab0}\\ \check{Z}_{ac1} = 1/3(\check{Z}_{ac} + a\check{Z}_{ba} + a^2\check{Z}_{cb}) = a\check{Z}_{ab1}\\ \check{Z}_{ac2} = 1/3(\check{Z}_{ac} + a^2\check{Z}_{ba} + a\check{Z}_{cb}) = a^2\check{Z}_{ab2}\end{matrix}\right\} \quad \text{.....(82)}$$

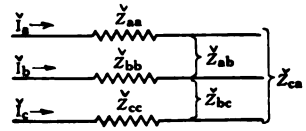


FIG. 11—SERIES IMPEDANCE CIRCUIT

Therefore

$$S(\check{Z}_{ac}\check{I}_c) = S^0(\check{Z}_{ab0}\check{I}_{a0} + \check{Z}_{ab2}a\check{I}_{a1} + \check{Z}_{ab1}\check{I}_{a2}) + S^1(a\check{Z}_{ab1}\check{I}_{a0} + a\check{Z}_{ab0}\check{I}_{a1} + a\check{Z}_{ab2}\check{I}_{a2}) + S^2(a^2\check{Z}_{ab2}\check{I}_{a0} + a^2\check{Z}_{ab1}\check{I}_{a1} + a^2\check{Z}_{ab0}\check{I}_{a2}) \quad \text{...(83)}$$

Using the $a$ phase as the first term in the sequence, the drop in the three phases, $S(\check{E}_a)$ is

$$\left.\begin{matrix}S(\check{E}_a) = S^0(\check{Z}_{aa0} + 2\check{Z}_{ab0})\check{I}_{a0}\\ + S^0(\check{Z}_{aa2} + (a^2+1)\check{Z}_{ab2})\check{I}_{a1}\\ + S^0(\check{Z}_{aa1} + (a+1)\check{Z}_{ab1})\check{I}_{a2}\\ + S^1(\check{Z}_{aa1} + (1+a)\check{Z}_{ab1})\check{I}_{a0}\\ + S^1(\check{Z}_{aa0} + (a^2+a)\check{Z}_{ab0})\check{I}_{a1}\\ + S^1(\check{Z}_{aa2} + 2a\check{Z}_{ab2})\check{I}_{a2}\\ + S^2(\check{Z}_{aa2} + (1+a^2)\check{Z}_{ab2})\check{I}_{a0}\\ + S^2(\check{Z}_{aa1} + 2a^2\check{Z}_{ab1})\check{I}_{a1}\\ + S^2(\check{Z}_{aa0} + (a+a^2)\check{Z}_{ab0})\check{I}_{a2}\end{matrix}\right\} \quad \text{.....(84)}$$

or

$$\left.\begin{matrix}S(\check{E}_a) = S^0(\check{Z}_{aa0} + 2\check{Z}_{ab0})\check{I}_{a0}\\ + S^0(\check{Z}_{aa2} - a\check{Z}_{ab2})\check{I}_{a1}\\ + S^0(\check{Z}_{aa1} - a^2\check{Z}_{ab1})\check{I}_{a2}\\ + S^1(\check{Z}_{aa1} - a^2\check{Z}_{ab1})\check{I}_{a0}\\ + S^1(\check{Z}_{aa0} - \check{Z}_{ab0})\check{I}_{a1}\\ + S^1(\check{Z}_{aa2} + 2a\check{Z}_{ab2})\check{I}_{a2}\\ + S^2(\check{Z}_{aa2} - a\check{Z}_{ab2})\check{I}_{a0}\\ + S^2(\check{Z}_{aa1} + 2a^2\check{Z}_{ab1})\check{I}_{a1}\\ + S^2(\check{Z}_{aa0} - \check{Z}_{ab0})\check{I}_{a2}\end{matrix}\right\} \quad \text{.....(85)}$$

The above equation gives the general solution regardless of the value of the impedances. Consider the special case in which the impedances are perfectly symmetrical.

$$\left.\begin{matrix}\check{Z}_{aa} = \check{Z}_{bb} = \check{Z}_{cc}\\ \check{Z}_{ab} = \check{Z}_{bc} = \check{Z}_{ac}\end{matrix}\right\} \quad \text{.....(86)}$$

Substituting in the equations for the symmetrical

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components of the impedances in equations (77), (79), and (82), the following is obtained.

$$\left.\begin{aligned} \check{Z}_{aa0} &= \check{Z}_{aa} \\ \check{Z}_{ab0} &= \check{Z}_{ab} \\ \check{Z}_{aa1} = \check{Z}_{aa2} &= \check{Z}_{ab1} = \check{Z}_{ab2} = 0 \end{aligned}\right\} \quad \text{.....(87)}$$

The general equation for voltage, equation (32) then reduces to

$$\left.\begin{aligned} S(\check{E}_a) = S^0(\check{Z}_{aa} + 2\check{Z}_{ab})\check{I}_{a0} \\ + S^1(\check{Z}_{aa} - \check{Z}_{ab})\check{I}_{a1} \\ + S^2(\check{Z}_{aa} - \check{Z}_{ab})\check{I}_{a2} \end{aligned}\right\} \quad \text{.....(88)}$$

This equation is quite significant. It indicates that zero sequence voltage drops are produced only by zero sequence currents, positive sequence voltage drops by positive sequence currents and negative sequence voltage drops by negative sequence currents. The three sequences are separate and distinct and do not react one upon the other. One can readily see the importance of such a fundamental relation.

Although this demonstration is limited to lumped self and mutual impedances the above relations may be shown to hold equally well for distributed constants, both inductance and capacitance. A rigorous proof for this condition is too long for presentation in these articles. A critical examination of the proof for the lumped constants would lead one to expect such relation.

To this point no mention has been made of rotating machine impedance; only static networks have been considered. Mr. Fortescue in his classic has shown that even for symmetrical rotating machines the different phase sequences do not interact one upon the other.

Because of their importance in the method of symmetrical components special names have been assigned to the coefficients of the currents in equation (88). The coefficient of $\check{I}_{a0}$ is called the "impedance to zero sequence currents", that of $\check{I}_{a1}$ the "impedance to positive sequence currents", and that of $\check{I}_{a2}$ the "impedance to negative sequence currents". For static networks, or machines with either lumped or distributed constants, the impedances to negative and positive sequences are equal; but in rotating machines these impedances are in general different, e.g., in induction motors the impedance to negative sequence currents is very nearly equal to the impedance with blocked rotor and changes very little with normal variations in slip, but the impedance to positive sequence currents varies considerably with normal variations in slip, being very high with low power-factor at no load.

These impedances are of very great practical importance, and may be measured experimentally with ease. The impedance to positive sequence currents of both series impedances and machine impedances are the impedances ordinarily used in calculations of balanced conditions. The impedance to negative sequence currents may be measured by applying voltages of reverse or negative sequence to the network or machine, while the impedance to zero sequence may be measured by connecting the three phases together and applying single-phase voltage to the group in parallel.

*(To be Continued)*

# Recent Developments in Steam Turbine Cylinder Joint Fastenings

J. B. WALBRIDGE
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IN VIEW of the continual trend of steam turbine development toward higher pressures, the subject of bolting of the high pressure cylinder has become one that requires special consideration. Within the ordinary range of pressures, where bolts of normal size and length may be used, the problem has been one of minor importance. In the case of machines designed for high pressures, however, large bolts of considerable length, spaced close together, are required.

Moreover, not only must special bolts be used, but the cylinder joint must be of special design in order to reduce the duty of the bolts as much as possible. With this end in view the horizontal cylinder joints of high pressure turbines are grooved, Fig. 1, inside the bolt line, and the groove is connected to the exhaust chamber in order to reduce the pressure difference across the outer portion of the joint. In this manner any leakage from within the cylinder to the groove is vented to the exhaust chamber and consequently the maximum pressure difference between the groove and the outside of the joint is the difference between the turbine exhaust chamber pressure and that of the atmosphere.

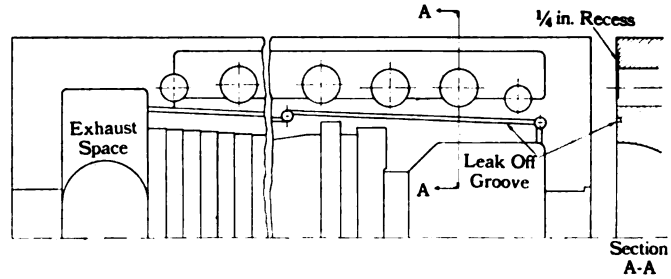


FIG. 1—HIGH PRESSURE TURBINE CYLINDER JOINTS ARE GROOVED TO RELIEVE LEAKAGE PRESSURES

In the latest designs, in addition to the groove, the cylinder joint has been relieved to obtain an area of joint surface such as will produce a joint pressure of 10 000 lbs. per square inch when the bolts are

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stressed to approximately 70 000 lbs. per square inch.

These developments have proved valuable aids in the production of satisfactory joints, but the feature of chief importance, and the most interesting one, has been the development of a system of bolting by which the bolts are stressed equally and to a predetermined degree, since this has been shown to be the most vital factor in making uniformly tight and safe high pressure joints. For this purpose bolts of special design and high grade material are used.

The bolts are made of chrome-nickel steel manufactured by the open-hearth or electric furnace processes. It is very tough and elastic, having a tensile strength of 140 000 lbs. per square inch, and an elastic limit of 90 000 lbs. per square inch. In the process of manufacture, the bars are allowed to cool after rolling or forging. They are then uniformly reheated to the proper temperature to refine the grain, held for sufficient length of time to insure complete penetration, and quenched in some medium under substantially uniform conditions. They are then reheated to the proper temperature for tempering or drawing back, held for sufficient length of time to insure complete penetration and desired structure, and quenched in oil. After straightening, they are once more uniformly reheated to within 50 degrees F. of the preceeding draw temperature, held for sufficient length of time to complete penetration and relieve stresses incident to the straightening operation, and cooled uniformly in air or oil.

This material will not stand the shocks attendant upon the time-honored method of "slugging" with spanner and sledge, and, further, it is not only difficult to make large bolts (3 and 4 inches in diameter) tight, but practically impossible to determine the stress to which they are being subjected unless special means are provided for the purpose.

The necessary means for tightening and for determining stress have been provided, by so designing the cylinder bolts that they may be heated, and drawn up while in the expanded condition; and by making it possible to measure accurately the length of the bolt before and after tightening, thus determining the amount of stretch.

These bolts have drilled through the greater part of their length a hole into which a micrometer gauge may be inserted for measuring the length. Sleeve nuts are fitted at either end of the bolt and these in turn are made with a central hole of such size as will admit the measuring device.

In bolting up the cylinder, the bolts are first tightened by hand and then released in order to take up the initial stretch. It will be found that the bolt does not go back to its original length after this first tightening. The length of the bolt is then measured, through the hole provided, by the measuring device shown in Fig. 2. This consists of a rod with spacing collars that will just fit into the hole. A sleeve is passed through the hole provided in the nut and rests on top of the stud or bolt. A micrometer depth gage is then placed over the sleeve and a reading taken from top of sleeve to top of rod. With the initial length of the bolt now determined it is tightened cold as far as possible and another measurement taken. Knowing the amount of the cold stretch given the bolt in the first operation, and the final stretch necessary to produce the bolt stress called for, the difference will be the amount of stretch that must be given the bolt when hot.

The bolt is then heated by means of an electric heating element contained in a tube of suitable diameter to fit the hole in the bolt, and operated from a 110 volt alternating-current circuit. It is now an easy matter to draw up the bolt, while hot, a sufficient amount to produce the desired stretch, when cold.

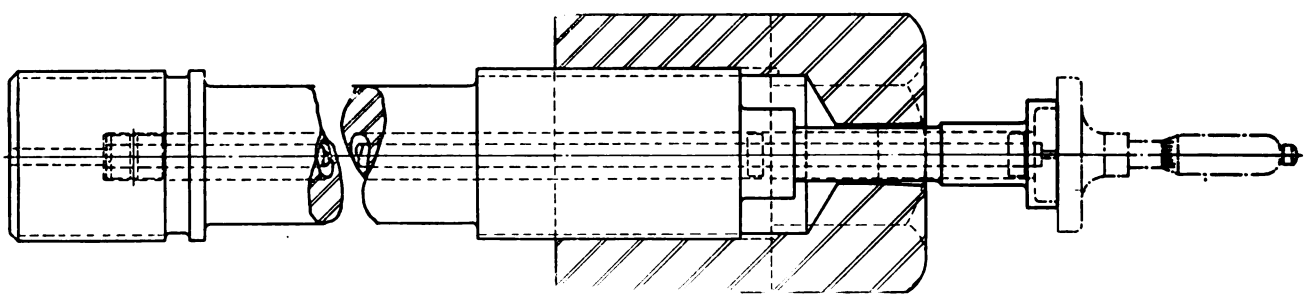

FIG. 2—THE LENGTH MEASURING MICROMETER INSERTED INTO A LONG BOLT

As six-thread nuts are used throughout, the amount the nuts must be turned, measured on a circle passing through the outer corners of the nuts, can be determined from the known diameter of the nut and the amount of stretch still required. For instance, if a final stretch of 0.110 inches is required in the case of a certain bolt and the cold stretch was 0.048 inches, the remaining stretch will be 0.062 inches. Assuming that this is a 3½ inch nut, the amount of rotation of a marked corner of the nut is found to be 0.1013 inches for 0.001 inch advance of the nut. This requires a total advance of the corner of 6.28 inches to give the remaining stretch of 0.062 inches.

It must be expected that, due to the compression of the metal surrounding the bolt holes, the final stretch checked after the parts are cooled off will not be so great as determined by the above method.

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It is, therefore, the practice to increase the amount the nuts are to be turned by approximately ten per-cent to allow for this effect.

In addition to the careful determination of stress in the material, if the bolt is long, it is essential that it stand with its axis central in the clearance hole and that the axis of the bolt be perpendicular to the face of the cylinder.

For this purpose there is provided a hardened steel washer with a centering lip, which is ground to a polished surfaces and the washers, nut, cylinder and threads are lubricated with cylinder oil and pulverized graphite. This is intended to reduce to a minimum the frictional resistance to turning of the bolt nuts when being tightened. It was found that if such provision were not made the long bolt would be pulled to one side of the clearance hole and that one side of the nut would chafe on the cylinder face, as a result of which the torque on the bolt would not be released when the tightening force was removed, and the bolt would remain wound up like a spring and bear unevenly under the nut face.

The process refinements described above, each in itself a small matter, in their totality have resulted in a method of cylinder bolting that produces dependable and satisfactory results and has eliminated annoying and destructive steam leaks under high pressure.

## Baby Synchronous Motors

THE world's smallest synchronous motors are used in the timing element of watthour demand meters. Recently in designing a new meter, because of space limitation, an even smaller motor than usual was required. As a result the motor illustrated was built, establishing a new record for smallness.

This motor, except for its size is not unlike previous watthour-meter motors. The motor current flows through coils around the stator,

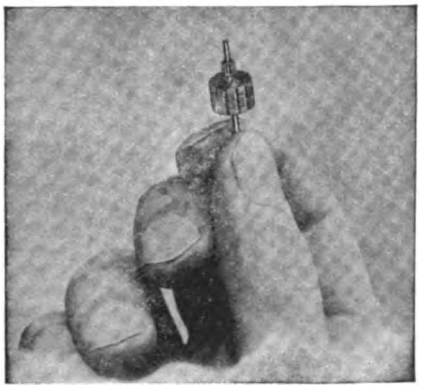

FIG. 1—THE OUTPUT OF THIS MOTOR ARMATURE IS OF THE ORDER OF A MILLIONTH OF A HORSE-POWER

starting torque being provided by the use of a shading coil The armature is notched. Thus at synchronous speed the poles, having less reluctance than the space between them, lock in position and rotate with the revolving field. This provides a simple means of securing a synchronous speed motor, though the torque obtainable is low. The motor drives the timing register through a gear train. It is supported on ball bearings, with 1-16 inch balls which do not seem small, but drop one and try to find it.

## The Functions of a Relay

THE protective relay is an electrical instrument, accurate in operation, sensitive in adjustment, and sturdy in construction, interposed between the main circuit or apparatus and the circuit-breaker in such a way that any abnormality in the circuit acts on the relay. The relay, in turn, after the proper discrimination as to the magnitude and character of the fault, causes the circuit breaker to function and thus relieve or protect the circuit or apparatus. The protective relay is used for three types of application:—Service protection, apparatus protection and automatic control.

### SERVICE PROTECTION

The most important duty of the protective relay is to protect the service against interruption. This may be done either by automatically sectionalizing an electrical system so as to disconnect the disabled section, or by automatically restoring the service after it has been accidentally interrupted. In large systems the main lines are usually so arranged, either by means of parallel feeders or loop systems, that each substation on the main system has two or more circuits over which power may flow from the generating station. Thus, when a fault develops on one of the circuits, it may be disconnected without entirely cutting the substation off the system. In smaller systems where small faults, which will clear themselves in a short time, are liable to occur, it is sometimes desirable to have a circuit breaker reclosed after it has tripped out. In such a case, if the fault has cleared itself, the circuit breaker will stay closed, but if, after two or three reclosures, it continues to open, then the fault is probably permanent and the line should be temporarily cut out of service.

### APPARATUS PROTECTION

Another use for protective relays is to protect apparatus, either by disconnecting it from service in case of failure,

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or the occurrence of abnormal conditions, or by functioning to remedy wholly or partially the abnormal conditions. In cases where a short-circuit or ground occurs in the winding of a machine such as a generator or transformer, it is usually necessary to have the apparatus disconnected. When the windings of a motor become overheated on account of overload, a relay may be used to set in operation some device for reducing the load over a period of time, thus allowing the overheated condition to adjust itself.

AUTOMATIC CONTROL

The recent phenomenal growth of automatic control has called for the development of a class of relays having mechanical and electrical characteristics similar to those of the protective relay, but whose function is to govern the automatic operation of the group of machines to which they are connected. These relays are called control or discriminating relays. They are used for automatically starting and stopping substations and isolated hydroelectric stations, governing their loading conditions and for other automatic control operations.

## The Permanence of Voltage Transformer Calibration

THE only thing which can affect the accuracy of an instrument potential transformer, without destroying the transformer, is a change in the iron. This would change the exciting current, which has a small but not negligible affect on the ratio and phase-angle errors. However, the silicon-steel which has been used in good transformers for the past twenty years is practically non-aging. It is safe to assume that the original calibration of a first-class modern potential transformer is permanent.

There may however be a temporary change which would affect the calibration of a current transformer. If the core has been magnetized, either by passing direct current through the coil, by opening the secondary circuit with current in the primary, or by a heavy overload on the primary, the iron loss and magnetizing currents may become abnormally high and the ratio and phase-angle errors may be slightly greater than normal. Such a transformer can be demagnetized and restored to normal condition by passing about 150 percent of normal alternating-current of any convenient frequency through the primary with the secondary connected to a resistance of 20 to 30 ohms and gradually reducing the resistance to zero. Great care should be taken not to come in contact with the secondary leads during this operation, as dangerous voltages may be induced.

## How to Plug Holes in Panels

WHEN changes or repairs are made on switchboard panels, holes are occasionally exposed by the removal of apparatus. To plug such holes on black marine finish slate or marble, the following process may be used:—Fill the holes with litharge and glycerine cement, pressing it in firmly and leaving an excess of cement at the top (about 1/8 of an inch) to provide for shrinkage.

The cement is prepared by thoroughly mixing litharge with lamp black and then sifting the mixture through a 50 mesh screen. A minimum amount of lamp black should be used, that is, only enough lamp black to give proper color to the cement should be added to the litharge. After sifting the mixture make a smooth paste by adding glycerine in the proportions of one part glycerine to three and one-half or three and three-quarters parts of litharge mixture, by weight; Since this mixture hardens rapidly, make only enough of it for the particular job. Once the mixture has begun to set, no attempt to thin it with glycerine should be made.

After filling the hole, allow the cement to dry for approximately twelve hours. Then rub it down to the panel level with a rotten stone rubbing brick, taking care not to injure the surrounding surfaces, after which the part plugged and the adjacent surface should be sprayed with lacquer and, when dry, rubbed down with fine sand paper or emery cloth. This operation should be repeated until a neat looking job has been made. Small holes may be plugged with plaster of paris and painted or colored to match the panel material.

Much of the success of this cementing process depends upon the grade of litharge used. The litharge must be of a good grade and should be free from or contain only a small percentage of red lead.

## Short-Circuit Protection for Synchronous Converters

A SYNCHRONOUS converter, like any synchronous machine, carries load by virtue of its rotor dropping back in its phase position an amount sufficient to pass the necessary load current through the impedance of its internal circuits. On large, 60-cycle converters, approximately seven times full-load current causes the rotor to drop back enough to pull out of step or slip a pole, if the load is not removed in a sufficiently short time interval. A synchronous, commutator type of machine cannot slip a pole under any considerable percentage of full voltage at the commutator without serious flashing. Hence, it is necessary to provide either sufficient minimum short-circuit resistance to prevent the current approaching pull-out value, or a high-speed circuit breaker to limit the current and relieve the converter of its excessive direct-current load before the rotor can drop back in phase position sufficient to pass excessive alternating-current through its windings.

Sudden interruption of excessive load or short-circuit current with an ordinary speed circuit breaker on any synchronous converter is conducive to flashing at the commutator. The net armature reaction in the converter is normally quite small, due to the mutual neutralizing effect of the alternating- and direct-currents. The machine constants affecting commutation are proportioned accordingly. The sudden interruption of a heavy direct-current load, with an ordinary slow-speed breaker, is followed by the flow of a correspondingly large alternating current tending to restore the rotor to its no-load phase position. The alternating current, flowing alone in the windings, produces a large uncompensated armature reaction, with consequent field distortion, excessive short-circuit currents under the brushes and high voltage between adjacent commutator bars. This results in heavy sparking or flashing. In most cases of flashover, the converter should be removed from service if possible until the commutator is smoothed, and all brush rigging thoroughly cleansed to remove all carbonized particles.

It has been found that in most 600-volt interurban and street railway service, satisfactory overall performance of machines can be insured by providing a definite, minimum value of short-circuit resistance. The maximum short-circuit current due to system faults is thus limited to a value which can be safely commutated during the period required for the opening of an ordinary circuit breaker or contactor of normal opening speed. The most common method of providing this resistance is to extend each feeder a sufficient distance from the substation before connecting to the trolley system. In a few cases where the trolley wire in itself possesses sufficient conductivity to carry all the current, it may be desirable to use grid resistors rather than to install a length of feeder copper.

It is difficult, if not impossible, to specify a minimum value of resistance which, in conjunction with low-speed circuit breakers, will prove satisfactory on all systems. Any synchronous converter, not provided with high-speed circuit breaker protection, will flash-over on dead short-circuit. The minimum resistance of the feeder circuit to the first point connected to the trolley, should be as low as is consistent

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with overall satisfactory performance under the frequency and severity of short-circuits encountered on the particular system under consideration. Final determination of the proper value of resistance will often resolve into a method of "cut and try".

Table I gives the recommended minimum values of positive feeder resistance (not including the negative return circuit) for use with modern, high-reluctance commutating-pole, 60 cycle, 600 volt railway converters. Motor-generators and 25 cycle railway converters will perform satisfactorily with the same values.

TABLE I—RECOMMENDED MINIMUM VALUES OF POSITIVE FEEDER RESISTANCE

| Converter capacity in kw | Feeder resistance ohms |
|---|---|
| 300 | 0.080 |
| 500 | 0.060 |
| 750 | 0.046 |
| 1 000 | 0.038 |
| 1 500 | 0.025 |
| 2 000 | 0.018 |
| 3 000 | 0.013 |

In providing the necessary resistance in feeders supplied by synchronous converters, the stability of the transmission line, the switching arrangement and load conditions must be given due consideration. The values as given will limit the current, due to the short-circuit at the first feeder tap, to an amount which can be safely carried by the machine over the period of operation of a circuit breaker of ordinary speed. However, if this current is totally interrupted by a single operation, the unit will tend to flash over, because of the subsequent lack of any commutating field to neutralize the excessive alternating-current which continues to flow in the windings.

Properly arranged switching equipment, so designed that the converter is relieved of the short-circuit current in two steps, is effective in preventing flashing. A suitable time element is introduced in the tripping circuit of the feeder equipment, so that the current is first reduced by the opening of an auxiliary circuit breaker or contactor-shunting, current-limiting resistance. The opening of the feeder circuit breaker then relieves the converter of the reduced current by opening the circuit altogether. During the period between the opening of the first and second circuit breakers, a certain amount of direct-current is present to neutralize the effect of the heavy alternating current flowing in the windings of the converter to restore the armature to its proper phase position. The presence of connected load on the station bus provides a corrective effect of the same nature which, in multifeeder stations operating at high load factor, may be sufficient. In manually-operated stations where the proper switch sequence cannot be arranged, and where the load conditions do not afford sufficient protection, higher values of minimum resistance may be required in the feeder circuits to secure satisfactory results.

The development of the high-speed, direct-current circuit breaker offers a means of protection to the synchronous converter from the effects of faults in the direct-current system. The high-speed circuit breaker is an air-break switch of the contactor type. It is designed to open its contact quickly enough to relieve the machine of its excessive load before the rotor can deliver its stored energy, and drop back in phase position sufficiently to pass an excessive alternating current through its winding. The unbalanced armature reactions and resultant flashing at the commutator which would result are thus prevented.

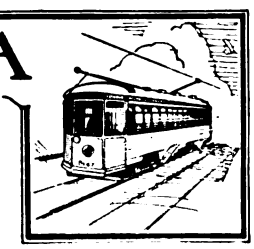
# RAILWAY OPERATING DATA

THE ELECTRIC JOURNAL

April 1928

The purpose of this section is to present accepted practical methods used by operating companies throughout the country.

The co-operation of all those interested in operating and maintaining railway equipment is invited. Address R. O. D. Editor



## Revamping Old Railway Motors with Modern Renewal Parts

The experience gained in improved designs, use of high grade materials and better shop methods as used in the construction of modern motors has in many cases been applied by the original manufacturer of the equipment to the manufacture of renewal parts for the older types of motors. Many operators who for financial reasons may not be in a position to replace their old motors by modern ones, can greatly improve the operation, and reduce the maintenance cost of their old motors by revamping them, using the improved renewal parts made available by the original manufacturer. Some of these are as follows:—

MODERN RENEWAL PARTS

1—*Shafts*—Motors that give trouble due to shaft breakage should be fitted with special heat treated axle or alloy steel shafts as they are from 45 to 75 percent stronger. These shafts have a tendency to wear less at the journal and will stand more severe abuse than the untreated shafts. Heat-treated shafts should not be welded.

2—*Spiders*—Some of the older types of motors were originally fitted with a spider having a separate pinion end and support, machined at the commutator end for a ring key to hold the laminations in place. This construction has given some trouble due to loose iron and it is advisable when rebuilding these cores to use the new one-piece spider. This spider and rear end bell are made in one piece of malleable iron or cast steel. They are machined at the commutator end for a heavy ring nut to hold the laminations together.

3—*Cores*—When the laminated iron is badly damaged, due to low bearings or grounded armatures, they should be torn down and rebuilt. When this is done, be sure that the iron is a tight driving fit on the spider or shaft. See that the original radial ventilating ducts are restored to help keep the armature cool. The 1/16 inch steel punchings at the ends should be spot welded in groups of three. This will provide a stiff finger plate to hold the rebuilt cores together and keep the iron from spreading.

4—*Commutators*—Use commutators that are made from hard-drawn copper bars, and high grade mica segments made from clean splittings assembled with the proper amount of bond and thoroughly seasoned. Assembled segments should have the correct machining in the *Vees* so as to make a solid commutator when it is heated and assembled under pressure on the bushing.

5—*Armature Coils*—In rewinding armatures, best results are obtained by using armature coils made from a good quality of copper wound to correct shape and insulated with a high grade fibrous material or a combination of fibrous material and mica. The insulation should be reinforced at crossovers and corners and the finished coil thoroughly treated by dipping and baking in a high grade baking varnish. In winding, the coils should not be twisted, bent or abused any more

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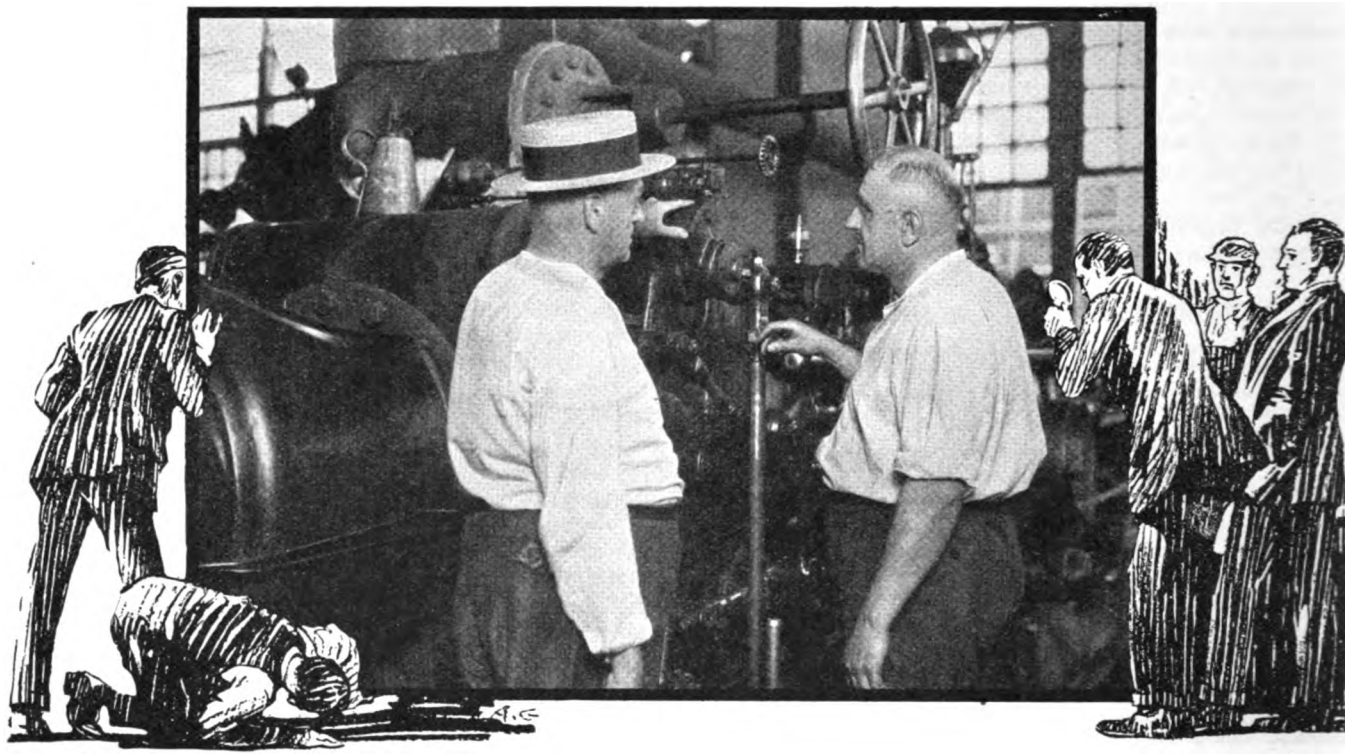

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3. Less "time-out" for repairs.
4. Fewer shut-downs due to bearing trouble.
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6. Lower rate of depreciation.
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than necessary. Insulating protecting pieces should be used at all points where leads or coils cross where there is danger of short circuiting.

6—*Field Coils*—There is considerable danger of damaging the copper on old field coils when they are put in a fire to burn off the old insulation, preparatory to rewinding and reinsulating. Modern field coils which should be used are impregnated in a high grade insulating compound. They are insulated with three to four overlapping layers of insulating tape and the finished coil dipped and baked at least three times, using a high grade baking varnish. Field coils for modern and revamped motors should be fitted with cable leads in place of the heavy brass terminals. It is of the utmost importance to spring support all field coils when assembled in the motor frame.

7—*Brushholders*—Various modern designs of brushholders are available for a great many of the older types of motors. Some of the improvements in these designs are better insulation, detachable carbon boxes, and a few fitted with dust caps to reduce carbon side wear. Most of these newer types of brushholders use the twin washer type of finger mechanism which has fewer parts, and all rubbing friction on the spindle is eliminated. This type, as shown in Fig. 1, finger can readily be applied to a large number of the present old types of brushholders which will improve their operation. On all brushholders, the porcelains should be kept clean and the shunts properly maintained. Brush tension should be adjusted to from 8 to 12 lbs. depending upon the service conditions. When the brushholders are spaced about 1/8 inch from the face of the commutator, they give best results in service.

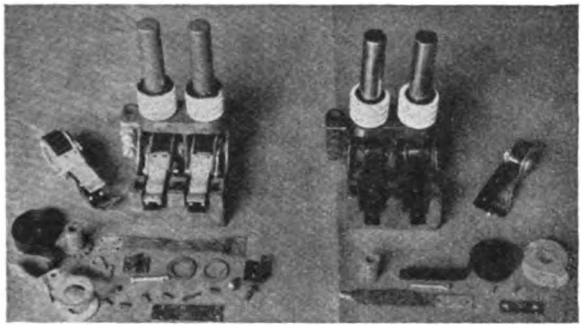

FIG. 1—AN OLD AND AN IMPROVED MOTOR BRUSH HOLDER

The rachet type finger (left) required 20 parts in its assembly. The new twin washer finger (right) is made from only eight parts.

8—*Carbons*—The use of high-grade carbon brushes, made by reliable manufacturers, who are equipped to furnish a unifom product is recommended. The cheaper grades not only give a short life but tend to wear the commutators more rapidly. The carbons should have a snug sliding fit in the carbon box and be carefully seated or bedded on the face of the commutator.

9—*Bearings*—The split armature bearings originally used on some of the older types of motors should be replaced by solid bearings. Those motors which originally used cast or malleable iron shells with a heavy lining of babbitt should be replaced by the more modern bronze shell with a 1/16 inch lining of high grade babbitt metal. For worn shafts and worn bearing seats in the housings, consider the use of standard oversize and undersize bore bronze bearing shells. These bearings should be fitted with oil grooves and the sides of the windows beveled to improve the lubrication. They should be given from 0.006 inch to 0.008 inch clearance at the shaft after pressed into the housings. Axle bearings, having iron shells, babbitt lined should be replaced by high grade bronze shells that are neither tinned nor lined with babbitt. Axle bearings when installed should have at least 0.015 inch clearance at the axle and under these conditions oil grooves are not required.

10—*Housings*—The split frame type of motor should be fitted with the through-bolt type of housings. These housings are made of malleable iron or semi-steel and are strong and durable and less liable to wear. The special heat-treated bolts used to hold these housings, are tough and strong, and, if threads wear, can readily be replaced by new bolts. A new type of oil sealed housing is available for certain types of motors. They give a constant supply of oil, keep out the dust and dirt, give an increased bearing life, and materially reduces the number of oilings required.

11—*High Grade Bolts*—Special heat-treated bolts should be used in connection with housings, axle caps, and frames of all railways motors. These bolts have 60 percent more tensile strength and are tougher and more dependable than standard hardware bolts. They will stand more abuse and are less likely to stretch or break in service. It is very important that lock washers be placed under the heads of all tap bolts and under the nuts on all through or stud bolts.

12—*Gear Cases*—The deep-drawn sheet-steel gear cases made in one piece are light and dependable. With their overlapping joints at the side, they afford better protection to the gears by keeping the dirt out and the grease in. Safety straps are not considered essential since there is less danger from broken supporting bolts with the lighter weights.

### IMPROVED METHODS

Not only should modern renewal parts be used in revamping old railway motors, but operators should take advantage of the improvements in shop methods as applied to the construction of modern railway motors. Some of these are as follows:—

1—*Banding Armatures*—Apply a strip of tin (tinned sheet iron) under each of the core bands, preferably place the binding clips on the coils under the core bands. Solder all bands with pure tin solder as it stands a high temperature.

2—*Dipping and Baking Armatures*—All repaired and rewound armatures should be dried out thoroughly and then

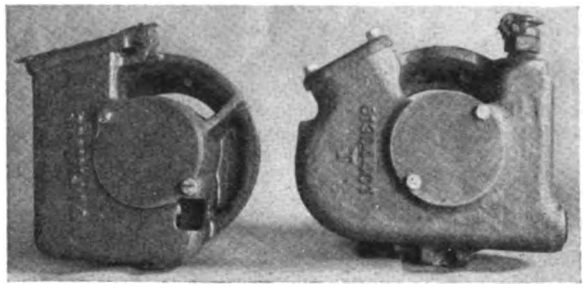

FIG. 2—TWO IMPROVED BEARING HOUSINGS

The standard through bolt housing (left) is fitted with through bolts instead of tap bolts. It is available for either standard or rebored motor frame seats. The oil sealed housing (right) works on the vacuum principle, which enables it to provide a constant flow of oil and keep out dirt and water. It requires very little maintenance and increases bearing and shaft life.

dipped in a high grade baking varnish, and baked from 48 to 60 hours at a temperature ranging from 95 to 105 deg. C. This will greatly improve the armature insulation.

3—*Undercutting Commutators*—Keep the mica on the commutators undercut from 3/64 inch to 5/64 inch deep, by the use of a special high-speed steel saw. This work should be checked by means of a depth gage. It is extremely important that all small slivers of mica be removed from the undercut slots.

4—*Spark Band Insulation*—Improved insulation at the spark band is obtained by applying a layer of soft twine, thoroughly shellacked, and ironed smooth with a hot iron. Three coats are necessary to make a thorough job. Then apply three coats of air drying varnish for the final finish.

5—*Better Babbitting of Bearings*—The babbitting of bearings can be greatly improved by the use of high grade tin base babbitt metal, shells carefully cleaned and tinned, and the babbitt poured at the correct temperature. Check all babbitted shells by giving them a sound test. Electric heated melting pots equipped with automatic temperature control should be used to insure the proper temperature for pouring the metal.

6—*Adjusting Armature End Play*—Excessive end play in the armature bearings should be taken up by the use of steel rings placed over the bearing back of the collar, rather than the use of a fibre ring between the bearing collar and the wiper ring.

JOHN S. DEAN.

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# The JOURNAL QUESTION BOX

Our subscribers are invited to use this department as a means of securing authentic information on electrical and mechanical subjects. Questions concerning general engineering theory or practice and questions regarding apparatus or materials desired for particular needs will be answered. Specific data regarding design or redesign of individual pieces of apparatus cannot be supplied through this department.

To receive prompt attention a self-addressed, stamped envelop should accompany each query. All data necessary for a complete understanding of the problem should be furnished. A personal reply is mailed to each questioner as soon as the necessary information is available; however, as each question is answered by an expert and checked by at least two others, a reasonable length of time should be allowed before expecting a reply.

2814—CARBON REMOVER—Do you know of any way to remove carbon that has accumulated in a bent brass tube where a wire brush cannot be run through it? This is a very small tube. The carbon has formed from vaporizing gasoline in the hot tube. Is their any acid that will remove it without destroying the tube?

F. H. (W. VA.)

If the tube is in such a shape that it cannot be heated red hot and the carbon burned out by passing air through it I would suggest that the tube be filled with benzene or kerosene and allowed to stand for sometime. This should loosen the carbon deposit so that a blast of air could blow it out.

H. M. E.

2815—SMALL POWER LINE PROBLEMS—I am putting in a lighting and power system for a series of three or four towns in the Philippines, to be operated from a hydro-electric plant, with fair prospects of adding one or two larger towns some fifteen miles away, at a later date. I have specified two 165 kv-a three-phase, 60 cycles, 2300 volt generators, with the intention of transmitting at 2300 volts primary and 220 volts secondary (which is practically standard in the Islands) but in view of the possible later addition of the larger load at fifteen miles distance, I have specified 2300/4600/8000 Y to 220 volt distribution transformers, so that when the distant load is connected, the same transformers can be reconnected in Y to give 8000 volt transmission, with an over-head primary neutral wire, grounded. The step-down distribution would be through single-phase transformers connected between one line and the overhead ground, for 4600 volts. The step-up at the plant from the 2300 volts generator to the 8000 volt line, would be through three single-phase 2300-4600 volt transformers, connected in delta on the 2300 side and in Y on the 4600 side, to give 8000 volts. No transformers will ever be connected in parallel on the low tension side. Now the question is, if the secondary distribution, which is largely a lighting load with a few three-phase motors, is unbalanced between phases, as it usually will be, will I be troubled with—(a) serious unbalancing of voltage in the different phases; (b) must or should the neutral of the Y connected 4600 volt side of the step-up transformers at the plant, be grounded? (c) will the unbalanced flow of primary current along the grounded neutral wire, or through ground itself, from one single-phase distribution transformer to another on the other phase, some distance away, interfere with ground return telephone lines which are already installed along the same roads and streets? I presume no serious harmonic effects will be caused by this scheme of connections. The use of this scheme of connections, if feasible, would allow me to build to 2300/200 volt standards for the present, and yet be always prepared to jump the voltage up, when (and if) my distant load is ready to connect, without increasing the size of line wire or buying new transformers.

L. H. T. (PHILIPPINE ISLANDS)

(a) There should be no serious unbalancing of voltage in the different phases for the arrangement described. (b). The neutral of the star-connected 4600 volt side of the step-up transformers should be grounded. If this point is well grounded and the loads are balanced as well as feasible, there will probably be no need of bringing the neutral wire back over the 15 miles from the load center to the station transformer. (c) There should be no serious harmonic voltages existing in the star-connected transmission line. The currents of the third harmonic series have a closed path in which to circulate in the delta primary of the station transformer and it is probable that the only voltages of this series existing in the transmission line will be due to the impedance drop caused by these currents flowing in the station transformer primary. This should be negligible. This means that the only current of any magnitude flowing in the neutral of the transmission line will probably be due to the unbalance of load and since this is of fundamental frequency interference effect should not be serious. With a circuit of this nature there is a possibility of interference from other factors such as unsymmetrical spacing, etc. but those mentioned above are generally the most important. In any system of this kind it is important that the loads be balanced as well as possible.

T. J. B.

2816—VECTOR DIAGRAM FOR SINGLE-PHASE LOAD—Fig. (a) shows a single-phase motor served from secondary of three-phase, star-delta bank of transformers through a polyphase watthour meter. The writer is at loss to draw a vector diagram showing which element of meter will give reversed rotation at, say, 45 degrees between motor current and potential. It seems that no matter which way we count voltages around the delta two of them are always opposite to the currents which they produce, which I believe is counted in the direction it will cause current to flow. Obviously if current is taken as 1 to 3 and voltages 2-1 and 3-2 are reversed we will get correct result but we would not reverse these two if we were considering a three-phase load and I do not see why the nature of the load should effect the interrelation of the applied voltages. An explanation of how to go about this problem and of the apparent inconsistency will be greatly appreciated.

L. R. S. (ILL.)

When a single-phase load is supplied from two terminals of a delta system, the current will divide in the delta inversely as the impedances of the two parallel paths. Since the impedance of each phase is the same, the phase across

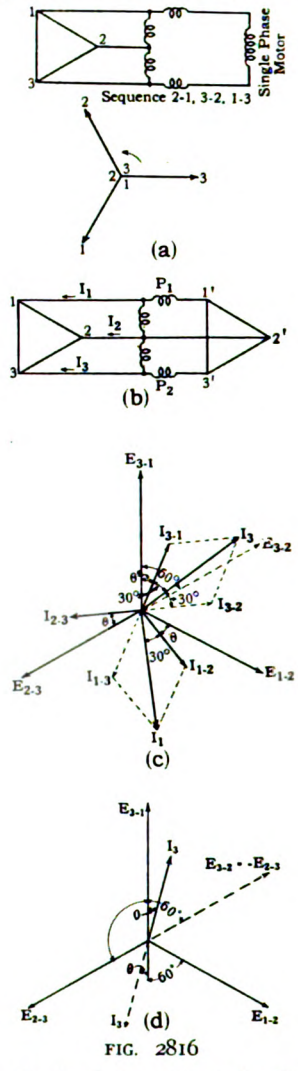


FIG. 2816

which the load is connected will carry 2/3 of the total current and the other two phases in series will carry one-third the current. The currents in the two branches will be in phase. For illustration, first consider a three-phase load connected to a delta source. Fig. (b). The numerals 1, 2 and 3 are the terminals of the load and the numerals 1′, 2′ and 3′ are the terminals of the source of supply, the wattmeter being

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connected in the proper direction to read positive on single phase. The vector diagram for this load is shown in Fig. (c). The notation for voltages and currents as to direction is given by the subscription: thus $E_{3,1}$ is the voltage drop 3 and 1. An inspection of the vector shows that the power $P_1$, indicated by the element in the lines 1-1' is: $P_1 = I_1 E_{1,2} \cos (30° + \theta)$ and the power measured by the element in line 3-3' is $P_2 = I_3 E_{3,2} \cos (30° - \theta)$. When the power-factor angle becomes 60 degrees, $P_1$ reverses. Now consider that the legs of the delta load 1-2 and 2-3 are removed, leaving the single-phase load 3-1 connected across the source of supply. The vector diagram for this condition is shown in Fig. (d). Now all the current flowing in line 3'-3 returns through line 1-1'. If the wattmeter connections are not changed, the element $P_1$ will reverse since the current has reversed. It is apparent from the vector diagrams that $P_1 = -I_3 E_{1,2} \cos (60° + \theta)$ and $P_2 = I_3 E_{3,2} \cos (60° - \theta)$. Any element will reverse when the angle between the current and voltage which it measures becomes 90 degrees. When $\theta = 30$ degrees, $P_1$ will reverse and at that power-factor will read zero. With the single-phase load connected, the current in the three phases of the source are in phase but the phase voltages are 120 degrees apart. The same holds true with the voltages as when considering a three-phase load; $V_{3,1'} + V_{2,3'} + V_{1,2'} = 0$; therefore, $V_{3,1'} = -V_{1,2'} - V_{2,3'}$, or $V_{3,1'} = V_{3,2'} + V_{2,1'}$. P. H. R.

2817—Testing Radio Transformers—Will you please describe a method for testing intermediate super-het transformers. I wish to match different makes of transformers or the same set or change the winding of one transformer to suit another make. I should also like to test the voltage given per stage. H. W. (IND.)

The most satisfactory way of testing intermediate frequency transformers is by the use of a tube voltmeter and an oscillator whose frequency can be varied over the frequency range of the transformers. By measuring the output voltage of each transformer with the oscillator coupled to the tube ahead of the transformer and varying the oscillator frequency, a resonance curve of the transformer is obtained. Each transformer should be adjusted so that the peak of its resonance curve occurs at the same frequency as the other transformers. The voltage amplification per stage is obtained by measuring, with a tube voltmeter, the voltage on the grid of the tube preceding and the grid following each transformer, and dividing the voltage on the grid following the transformer by the voltage on the grid preceding. G. L. R.

2818—Ground Detectors—(a)—What is the most practical or commonly used type of ground detector for a 440 or 550 volt, three-phase, three-conductor, non-grounded bus supplying power to a large industrial plant? (b) Are ground detectors often installed on such systems? (c) Will an electrostatic ground detector function properly on such low voltages? (d) Is a ground detector of any value on a three-phase, three-wire system with grounded neutral? J. R. L. (PENNA.)

(a) Three strings of five 110 volt lamps each star connected with neutral grounded is a satisfactory ground detector for such a system. (b) There is no general practice in installing ground indicators on such systems although it is good policy to do so. (c) Electrostatic instruments are not very satisfactory on such low voltages. (d) A ground detector is of no use as a ground is always a short-circuit on one phase. B. E. L.

2819—Calculation of Wound-Rotor Current—Please give a practical method for calculating the current in the wound secondary of an induction motor. C. E. B. (KY.)

A convenient method of calculating the secondary current of a wound-rotor induction motor is to calculate first the secondary voltage between rings, when the rotor is stationary with rings open, and normal voltage impressed on the primary, in which condition the action of the motor is the same as that of a polyphase transformer. This open circuit voltage between rings of a motor connected three phase in both primary and secondary may be calculated from the formulae:—

$$V_2 = \frac{V_1 \times T_2 \times C_2 \times K}{T_1 \times C_1}, \text{ where}$$

$V_2$ = secondary volts between rings.

$V_1$ = primary volts between rings.

$T_2$ and $T_1$ = effective series turns in secondary and primary respectively

$$= \frac{\text{turns per coil} \times \text{number of coils}}{\text{Numer of parallels in connection.}}$$

$C_2$ and $C_1$ = chord factor of secondary and primary windings respectively = sine (90 deg. × percent pitch of coil). For delta primary and secondary, $K = 1/1 = 1$. For star primary and secondary, $K = \sqrt{3}/\sqrt{3} = 1$. For delta secondary and star primary, $K = 1/\sqrt{3} = 0.577$. For star secondary and delta primary, $K = \sqrt{3}/1 = 1.73$. Since at synchronous speed the rotation of the secondary conductors produces the same rate of change of primary flux through the secondary coils, as is produced by the alternations of the primary flux at standstill, the voltage as calculated above also represents the counter e.m.f. generated in the secondary winding at synchronous speed. This counter e.m.f. varies directly with the speed and for any output is equal to $V_2 (1-s)$ where $s$ equals percent slip at this output. The secondary voltage can, of course, be measured by measuring the voltage across the secondary terminals when they are open—with normal voltage impressed on the primary. Since, for an induction motor, the same as for a direct-current motor, the output in watts is equal to the product of the counter voltage and the total armature current, the amperes per ring of a three-phase secondary for a given output are equal to

$$\frac{746 \times \text{hp output}}{\text{counter voltage} \times \sqrt{3}}$$

This is neglecting the phase displacement between the rotor voltage and current which displacement is negligible at normal speed. Then substituting the value of the counter e.m.f. as found above, the amperes per ring for a given output will be equal to

$$\frac{746 \times \text{hp output}}{V_2 \times (1-s) \times \sqrt{3}}$$

This neglects several minor factors, which affect the rotor current and voltage, but for all practical cases the value found as above is sufficiently accurate. O. C. S.

2820—Contamination of Transformer Oil—1—This climate is rather humid and the atmosphere contains considerable salt from the ocean. A certain bank of transformers is cut in and out of service frequently which probably causes considerable breathing. There are no *CaCl* breathers on these units. Failures are frequent due to insulation breakdown. Is it possible the salt could form an acid in the oil after entering during the breathing period? b—Rubber hose has been used for a couple of years on the filtering apparatus for these latter transformers. Several sets of hose have gone to pieces from the effect of the oil, as was to be expected, but is there any possibility that the rubber through its sulphur content could form an acid in the oil and cause insulation failures? c—Do you have any special instructions for transformers operating in tropical islands where there is salt content in the air? J. P. T. (HAWAII)

The climate referred to gives a combination of rather extreme moisture in the air as well as salt. Some of this salt undoubtedly is in the form of fine particles of solid material. As these salt particles and the moisture in the air are taken into the transformer the oil is contaminated. We do not think the salt in itself would be particularly harmful but that the moisture is the serious cause of trouble. The salt, however, being hygroscopic, may concentrate this moisture in places in the transformer winding which will lead to break downs. We would recommend the use of a breather with tight joints on the transformer case to keep out the salt and the moisture. Frequent filtering of the oil will undoubtedly help. We do not believe that the sulphur carried into the oil from the rubber hose forms a considerable part of the trouble in this case. E. G. R.

2821—Changing Mine Locomotive Trolley Heights—We have a mine locomotive which we wish to use outside the mine. The locomotive trolley is built to operate from a trolley wire five feet above the rail; the outside trolley wire from which we desire to operate is 12 feet from the rail. What changes or alterations in trolley pole, base and spring would you suggest? F. H. (W. VA.)

In order to use the present trolley base with 12 ft. height instead of 5 ft. as originally designed, it is necessary to make several changes. The center of gravity of the pole will be of course further out and the spring pressure will act with a greater moment arm, thus requiring a heavier spring to balance the pole load and maintain wire pressure. By making the spring wire larger, the spring cylinder would have to be longer in order to get in the right number of coils to balance the load. In order to give exact information, it would be necessary to have information as to the wire pressure required, weight of the pole and all connected parts with center of gravity,

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This information would be necessary in order to redesign the spring, with the consequent redesigning of other parts. O. P. A.

2822—Variation of Synchronous Converter Direct-Current Voltage by Changing Field Excitation—How far is it permissible to depart from unity power-factor in the operation of a synchronous converter, running at 100 to 110 percent load continuously. The rotary converter is rated 2500 kw, 5000 amperes, 500 volts, and is operated at about 530 volts, I wish to reduce this voltage to 515 if possible without changing transformer taps or reducing the transmission line voltage. I realize that a synchronous converter is meant to operate at practically unity power-factor but have not been able to find any definite statements as to just how far this may be departed from with safety. Fig. (a) shows some curves I took while varying the direct-current voltage of excitation and I would like to have your comments on these, particularly with regard to the increased efficiency that is shown with the lower voltage. S. H. B. (N. Y.)

The subject of synchronous motor copper loss while operating at less than unity power-factor has been discussed in an article "Synchronous Converter Copper Loss" by Lee and Hildenbrand,

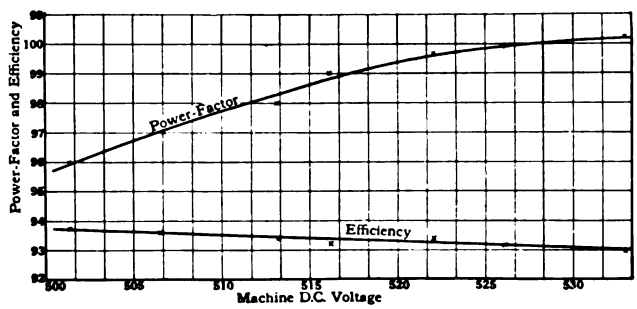


FIG. 2822 (a)

in The Journal for March, 1926, pp. 110 to 112. In this article curves are given showing the heating of a converter operating at various power-factors compared with that of a generator. Curves for single, two, three and six phase converters are included. From these curves it is seen that, at 98 percent power-factor, the heating of your converter (assuming it is six-phase) is only slightly greater than when operating at unity power-factor. As the power-factor is lowered the heating increases, the heating of the end or top coil increasing much more rapidly than the average heating. The limiting conditions, then, are the heating of the tap coils and commutation. The curve submitted showing an increase in efficiency below 530 volts, even though the power-factor is dropping off, is no doubt occasioned by the fact that this machine was designed for only 500 volts normal service and that extremely heavy saturation in the iron is necessary to obtain 530 volts. The reduced field and core losses, therefore, which are obtained when dropping down below 530 volts would account for the increase in efficiency being obtained at the normal voltage of 500. If your curves had been extended below 500 volts you would find that efficiencies would begin to decrease. R. H. N.

2823—Unbalanced Single-Phase Loads—An 11 mile transmission line is to be installed for which we have two choices of voltage. The first is to generate at 2300 volts, three-phase and step up to 4600 volts at the generating station, transmit at 4600 volts for 11 miles and distribute single-phase by stepping from 4600 to 230 volts using primary transformers connected in delta with single-phase secondaries Our second choice which we prefer, is to generate at 2300 volts and step up to 4600 volts but to connect our transformers in star on the high tension side to get 8000 volts transmission. We want to distribute single-phase current at the receiving end, placing three 4600 volt transformers connected in star to operate on 8000 volts. The transformer sizes will be one of 10 kv-a on one line; one of 7.5 kv-a on another line and two of 5 kv-a on the third line. The load may not be evenly distributed as each single-phase line will supply lights to three different sections of town and there is no possibility of properly balancing loads. The generators will have a capacity of approximately 150 kw and will supply other balanced load. Can this transformer connection be made without harm? H. L. R. (Philippine Islands)

Either of the transformer connections outlined can be made and satisfactory operation obtained providing certain precautions are taken. If the transformers are to be connected for 2300 to 8000 volts step-up and 8000 volts to 2300 step-down with the high tension side connected star and the low tension side operating with single-phase secondaries both the star connected side at the receiving end and at the sending end of the transformers must be grounded or the two neutrals interconnected by means of a ground wire of sufficient capacity to carry the unbalanced current. If an attempt is made to operate the transformers with single phase loads when the secondaries are not connected either in delta or star, only magnetizing currents can be taken by the transformer since one single-phase secondary is attempting to take load from the corresponding phase of the star-connected primary which is in series with an unloaded phase. The neutral of the high tension side at both sending and receiving end should be solidly grounded or the neutrals interconnected by means of a ground wire. The effectiveness of grounding the neutral of course will depend upon the resistance and reactance of the earth return and also the type of ground made. If the earth resistance is high, the neutrals should be interconnected by means of a ground wire. The operation of the transformers connected in star should prove satisfactory and the unbalance due to unequal load on the different phases should not appreciably affect the proper operation of the system as a whole. If the secondaries are connected in delta it will not be necessary to ground the high tension side. P. H. R.

2824—Transmission Line Reactance—Please explain how to calculate the percent reactance on a 100 000 kv-a base, of one mile of three single conductor 300 000 cm. copper cables (standard strand) forming a three-wire two-phase 2400 volt system, the wires being arranged at the vertices of a right isosceles triangle with the equal sides 5 in. long and the base 7.07 in. Frequency is 60 cycles. C. F. K. (Penna.)

The reactance per mile per phase can be obtained from Table XI, "Electrical Characteristics of Transmission Circuits" by Nesbit, for 300 000 cm and 5 inch spacing between wires of the same phase to be 0.369 ohms. The relation between ohmic and percent reactance is given by the formula:—

$$X_{ohm} = \frac{1000\ E^2\ X\ \text{percent}}{kv\text{-}a}$$

$E$ is the voltage per phase in kv. For the present case we have 2.4 kv between the outside and common conductor of each phase. Kv-a is transmitted power per phase, i.e., 50 000 for the present example. Therefore the percent reactance can be calculated as follows:—

$$X\ \text{percent} = \frac{X_{ohm}\ kv\text{-}a}{1000\ E^2}$$

$$= \frac{0.369 \times 50\,000}{1000 \times 2.42}$$

$$= 3.2$$

$$= 320\ \text{percent}$$

CHECK:—The current per phase is $50\,000/2.4 = 20\,800$ amperes. The drop per phase per mile is $20\,800 \times 0.369 = 7\,680$ volts. Therefore reactance is $7680/2400 = 3.2$. G. W. H.

2825—Milliameter as A.C. and D.C. Voltmeter—I have a milliameter (100 MA) which I am using as a direct-current voltmeter by inserting a 10 000 ohm resistance in series. With this arrangement I can read up to 1000 volts. 1—What will be the percent error by using the same arrangement to read 60 cycle alternating current? 2—What will be the percent error by using a non-inductive resistance instead of the Lavite resistor? L. B. S. (Penna.)

At 60 cycles the inductance of the Lavite resistor is negligible. The 100 milliameter instrument has an approximate resistance of 150 ohms and an inductance of 0.120 henry. Therefore the reactance at 60 cycles will be approximately 45 ohms. This reactance is negligible compared to the 10 000 ohms series resistance and therefore there will be no practical difference in the reading direct current or in reading 60 cycles alternating current. Please note that the 150 ohms resistance of the meter will be added to the series resistance making the total resistance 10 150 ohms instead of 10 000 ohms. The meter will therefore read 1.5 percent low. L. S.

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# THE ELECTRIC JOURNAL

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## Electricity in the Coal Industry

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Westinghouse Electric & Mfg. Co.

THAT the coal industry is one of the larger basic industries of this country and a continuous user of and natural customer for electrical machinery has always been before electrical manufacturers. A prosperous coal industry is the wish of electrical manufacturers, for the time has arrived when mines are planned to be electrically equipped.

Industry generally has been won to the idea of mass production, the mechanical handling of the raw as well as finished material, the use of machinery to replace back-breaking manual labor—and nearly always the motive power is electricity. Coal is an abundant natural resource, easily recoverable from the earth. Hence, this industry has been late in feeling the effect of contracting markets due to competing fuels. That condition unfortunately is now present and is concurrent with maximum productive capacity, excess of labor and low prices for coal, which threaten the very life of many companies. Hence, the movement toward mechanization in an effort to cut costs.

Mechanization means an improvement in production methods and a change in the layout of mines to accommodate the increased tonnage from a more restricted area. It introduces problems of transportation and power distribution, as well as of safety.

Transportation is particularly important with mechanization, and has brought into being room hoists and different types of conveyors. The coal picked up by loading machines must be carried away; and it has been found that in many cases, whatever type of gathering equipment is used, more speed and longer trips must be had in the main haulage ways to give a proper circulation of the cars from the loading point to the discharge point. This requires larger and faster locomotives. This in turn requires larger motors, more of them, and sturdier control. It also means experience in building these larger equipments into the mechanical parts of the locomotive so as to have a well-balanced design.

In many cases, a change in the size of main-haulage equipment and a rearrangement of the mine requires different equipment in the substations. This allows the introduction of economies of operation and attendance which were not possible where the workings were more widely scattered. Such a condition is ideal for automatic substations, which can be made even more accurate and positive in operation than those operated by hand. Though slightly more expensive in first cost, automatic stations soon save their extra cost in labor saved. By the use of some of the later developments, these can be operated from a central point and made to keep their own records.

In the matter of safety, all are interested. Though some mines are classed as gaseous, equipment is now available which is protected against the possibility of exploding surrounding gas. Not only loading machines, conveyors, pumps, room hoists, rock dusters, etc., can be so equipped, but the locomotives themselves.

Automatic control of other of the standard equipment of mines, and safety devices operating automatically, do much to minimize the possibility of accident and delay, and at the same time offer the opportunity of further mechanizing the mine equipment.

As the different requirements arise in the progress of mechanizing the mines, the electrical manufacturer will be found ready and willing to do his bit toward reducing the production and preparation costs of coal.

## Recent Developments in Mine Mechanization

GEORGE B. HARRINGTON
President,
Chicago, Wilmington & Franklin Coal Co.

DURING the past few years mechanization in coal mines has made great progress in the one direction which still offers the greatest possibilities of relief from human physical effort; namely, in the actual loading of the coal into the mine cars. Prior to this recent development, mine mechanization had made advances in many directions;—in the transportation of the coal, the mine mule now being replaced almost entirely by the electric haulage locomotive; in the elimination of the hand labor of snubbing, the work of snubbing being almost completely taken over by the electrical undercutting machine; and in many other ways, such as hoisting, ventilating, pumping, etc. It was not, however, until the last few years that the effort of the electrical and mechanical engineer has been directed to the replacing of the hand work of loading the coal, by mechanical devices.

There are, of course, many obvious difficulties to the introduction of a machine which would replace this physical effort. To begin with, the conditions under

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which the machine must operate are tremendously varied and widely separated. The machine must, therefore, in addition to being mechanically strong and efficient, have great mobility, so that it can be moved easily from one part of the mine to another. The service of supply for the machine and the proper cleaning of the coal are also problems which have caused considerable difficulty.

However, if the progress for the past few years can be taken as a criterion, it is not too much to expect that in a relatively short time the loading machine and its method of operation will become perfected so that, in mines of the future, electrically-operated loading devices will have almost completely replaced the physical effort of loading coal by hand.

## Electricity, Permissible Equipment and Mechanization

L. C. ILSLEY
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U. S. Bureau of Mines, Pittsburgh Experiment Station

IT is hard to visualize conditions in coal mining as they were before the introduction of electricity. It was indeed a large business, but was carried out laboriously and slowly as compared with mining of today. The introduction of electricity put new life into the old job of mining coal, speeded up production, increased output and reduced costs.

Coal mining in the old days had its hazards—gas explosions, roof falls, explosion hazards and haulage accidents. Electricity did not do away with these, but it added a real hazard of its own—namely, the electric arc. Permissible equipment became a necessity in this new order of mining, if life and property were to be safe-guarded.

Now we are in the midst of another great change which may be termed intensified mechanization. Electricity, owing to its adaptability and flexibility, is entering into every part of this newest phase of the coal mining. And because electricity is taking such a prominent part, and because the zone of this increased activity is where it is, permissible equipment also is taking its place in the front ranks.

In the mechanization of mines, with its accompanying enlarged and manifold use of electric equipment, four things stand out which may be considered under four headings—location, complication, circuits and dust.

The location, or active zone where nearly all of this intensified mining is taking place, is that area near the face where the coal is freshly mined and where gas is liberated and kept in safe dilution only by carefully planned schemes of ventilation. Any interruption to this ventilation creates a hazardous condition in many mines.

Complication results from the number of pieces of electrical equipment used on a single outfit, and and from the number of outfits used. Some electrical appliances have as high as ten compartments, all capable of igniting gas if not specially designed. Again, the number of units of electrical equipment in a given area is in some cases from five to ten times that of a few years earlier.

The wiring necessary to bring power to these units and to facilitate their control is a real problem when approached from a safety standpoint. No satisfactory solution has been found for safely handling stationary wiring or the trailing cables used in such quantities today. It is also difficult to impress the users of electrical equipment with the seriousness of conditions as they now exist.

The dust hazard has been greatly increased in connection with loading and conveying equipment. The only solution of this hazard would seem to be a thorough wetting of coal at the loading points.

It is believed that a careful consideration of the four points briefly discussed will convince one of the necessity of using permissible equipment in the face zone of gassy mines. Even this is becoming so complicated in design and with respect to wiring that its safe maintenance is a huge task, requiring constant watchfulness and rigid discipline.

## A Demon Enslaved

CHAS. R. RIKER

CENTRIFUGAL force enters largely into the action of any rotating machine. It is a foe to be watched most carefully when a water-wheel is suddenly deprived of its load and begins to accelerate towards double its normal speed. In machines of high peripheral speeds, especially, it is a veritable demon of mischief, being held in check only by the stoutest of materials.

This same force has, however, been converted into a friendly ally in many types of machinery, bending its back stoutly to the lifting of water or the compressing of gases in pumps and blowers; governing the speeds of prime movers with a tireless constancy; cutting its own throat, so to speak, by shutting off the source of power in case of overspeed.

Our relation to this particular demon is a typical repetition of the whole history of man's relationship to natural forces. The more he understands them and gains control over them and learns to use them, the more nearly he becomes an Olympian god, with superhuman powers; and the more free he is from needing to sacrifice to the powers of darkness.

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A ONE AND THREE-QUARTER YARD, FULL-REVOLVING, ELECTRIC SHOVEL

# The Electric Shovel

J. E. BORLAND
General Engineer,
Westinghouse Electric & Mfg. Co.

THE use of electricity for power shovels has been increasing rapidly, as a result of certain marked operating advantages over steam which have been amply demonstrated in service. As in the case of most departures from the beaten path, however, a considerable amount of prejudice and inertia had to be overcome before the electric shovel became firmly established in such a favorable position. The steam shovel was, in general, successful and had found extensive application as it provided a means of economical excavation and movement of material. Steam shovel design had been brought to a fairly stable point and the characteristics and limitations of the steam machine had come to be well understood before attempts were made to electrify the shovels. It was apparent that several objectionable features of steam operation would be eliminated or minimized with electric power, but there was a natural hesitancy on the part of many operators experienced with steam shovels to change over to a system as yet unproven.

In consequence, there was a transition stage af the beginning of which electric drive was regarded more or less as an experiment. Careful investigations and thorough tests were conducted by numerous operators to determine the merits of electric power before adopting it on an extensive scale. Following such investigations, many large operators of power shovels have adopted electric drive. Some operators with long experience with steam shovels have found it economical to supplant them entirely with electric shovels, others are following a plan of replacement as rapidly as conditions permit. Comparative records of steam and electric shovel performance and costs under conditions as nearly alike as it is possible to obtain in practice are decisively in favor of the electric shovel in almost every case.

While there will be always some places where the electric power shovel cannot be conveniently applied, the present trend is toward its almost exclusive use on permanent projects, such as open-pit mining, strip mining, quarrying, etc. The advantages of electric drive are not confined to these large operations alone, however, as it has been used extensively on excavating machines employed in construction of canals and dams, in irrigation work, in smaller quarries, in the rehandling of stock pile material, etc. With the extension of distribution systems, and the availability of power at reasonable rates, the electric shovel can be advantageously used on any work where economy, reliability and continuity of service are important.

A number of factors contribute to the better economy of the electric shovel, the most important being the lower costs of labor, power, maintenance, repairs

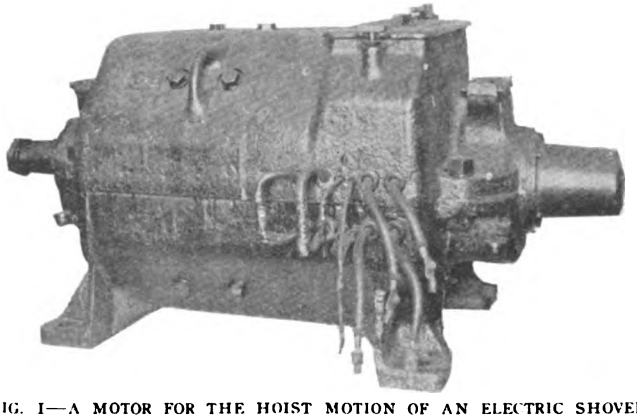

FIG. 1—A MOTOR FOR THE HOIST MOTION OF AN ELECTRIC SHOVEL
This motor, mechanically, is of the steel-mill type, and is notable for its ruggedness and ability to withstand heavy and sudden load.

and material. Of these, the saving in labor is usually the largest item. The modern electric shovel is designed for operation by one man, thus eliminating the fireman and frequently one or two pit men who are employed on the larger steam shovels, in passing coal and water. Records show savings of from 25 to 50 percent in costs of total operating labor, depending upon the type and size of shovel and nature of the

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work. The electric shovel operator, with a little experience, can make minor adjustments and repairs to the equipment, so that only the occasional service of an electrician is required for more thorough inspections and replacements.

Records of electric shovel operations show that the power consumption ranges from 0.25 to 0.5 kw hrs. per cubic yard for low lift and railroad type shovels to from 0.5 to 1.0 kw hrs. per yard for high lift shovels and draglines. With the type of shovel fixed and power rates known, the item of power cost for electric drive can be predetermined with fair accuracy. The cost of steam power is not so readily estimated, however, as it is subject to much wider variation, because of fluctuation in price of fuel and the heavy additional charges which are sometimes necessary for transportation and delivery to the shovel. The conversion of fuel into mechanical power on a steam shovel is a relatively inefficient process, coal consumption may be upward of eight pounds per yard of material handled. It frequently happens, also, that the cost of steam shovel operation is increased greatly by the condition of the water supply. This is reflected mainly in the charges of high maintenance and time lost in cleaning boilers and repairing damage caused by poor feed water. The determining factor in changing from steam to electric shovels, quite often, is the inability to keep the steam shovels in anything like steady service because of a lack of suitable feed water. While the added expense caused by poor feed water are usually included with the maintenance and labor charges, electrification almost invariably shows a material saving in cost of power. Data from reliable sources show savings of from 50 to 80 percent.

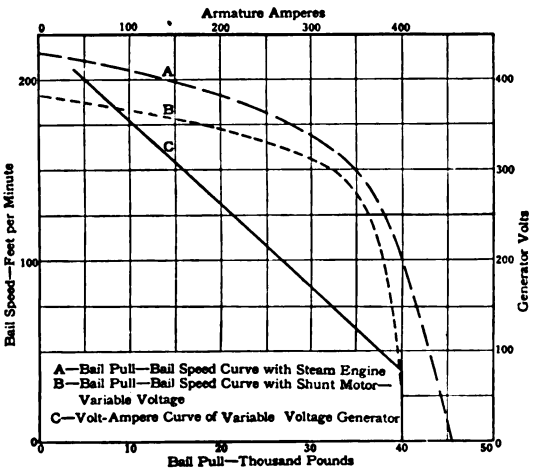


FIG. 2—COMPARISON OF SHUNT MOTOR AND STEAM-ENGINE CHARACTERISTICS FOR SHOVEL DRIVE

The supply of electric power in most systems is highly dependable and the time lost through power interruptions or electrical troubles is ordinarily much less than that lost by the steam shovel due to low pressure, leaking or broken steam or water lines, delays in coaling and waiting for coal, water or steam. This is particularly true when maintaining the supply of fuel or water to the steam shovel is difficult and when the shovel is required to operate in freezing weather.

While the steam shovel may be as fast as the electric shovel for short periods, the ability of the electric shovel to maintain its fast operation steadily with a minimum of interruption enables it to handle more material per shift than the steam machine. The electrified power shovel is a cleaner, more orderly machine and is more easily maintained. The absence of smoke and the comparatively quiet operation are desirable where the work is in a city or town. The modern electric shovel equipment is highly simplified and sturdy, and the troubles that do occur are usually corrected quickly and with little expense. Furthermore, electrification has resulted in a mechanically stronger and more substantial shovel, as it was found that steam shovel design was not adequate for electric drive. Recent improvements include the use of better gearing and methods of lubrication. In some cases double-helical or herringbone gears have supplanted spur gears, particularly on high-speed shafts where the greatest benefit is derived from eliminating noise and vibration. By reason of such improvements, along with the comparative simplicity of the electric shovel, with an absence of reciprocating motions and freedom from boiler troubles, the cost of repairs and renewals is materially lower than on the steam shovel.

It was early recognized that the open-throttle speed-torque curve of the steam engine, which is of the general shape shown by curve *A* Fig. 2, is ideal for power shovel operation. The maximum torque is inherently limited to a definite value, determined by the steam pressure, piston area and gearing, so that in heavy work the speed is automatically lowered until the maximum effort is developed with the engine stalled. With removal of the obstruction the engine accelerates rapidly, and at light loads runs at high speed. In the development of electrification, various methods were devised to provide similar characteristics in the electric drive. With the latest type of electrical equipment, using a modification of the variable voltage system, this feature is obtained automatically in a very simple manner. This system was first applied to power shovels about seven years ago, and has since been used extensively on all except the smallest sizes.

In the variable-voltage system each of the three main motions of the shovel, hoist, swing and thrust, is driven independently by a direct-current motor which receives power from an individual generator forming part of a motor-generator set mounted on the shovel. The motors employed are generally of the type known as mill motors, which have been applied widely on steel mill auxiliary drives, material-handling machinery, and other service requiring the utmost in motor sturdiness. This type of motor is noted for its substantial construction, both mechanical and electrical. It is the usual practice to use for the hoist an open or ventilated motor. An enclosed motor, such as that

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generally used for the swing and thrust, is shown in Fig. 1.

Motor frames are steel castings of heavy section, split horizontally to permit removal of the top half and facilitate inspection or replacement of internal parts. A rigid support is provided by wide-spread feet, integral with the lower frame half, which insures

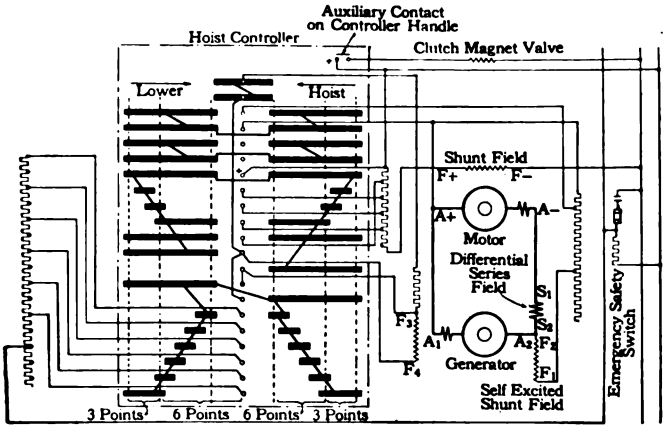


FIG. 3—A SCHEMATIC CONTROL DIAGRAM FOR A GENERATOR AND MOTOR ON A POWER SHOVEL

against vibrations when the motor is carried on a stable foundation. Armature and field windings are insulated with mica and asbestos, permitting the motor to operate safely at high temperature. All windings are braced and banded to avoid movement in service which would possibly chafe and damage the insulation. Successful commutation under the high and sudden overloads which occur in power-shovel service is provided for by correct design using laminated poles for both main and commutating fields.

Either series, shunt or compound fields are applicable on motors of a variable-voltage power-shovel

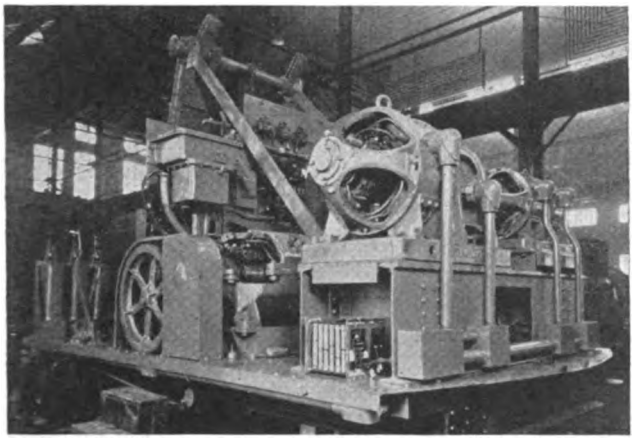

FIG. 4—A SHOP VIEW OF A SHOVEL CAB ASSEMBLY

Showing the extremely compact arrangement of the equipment made necessary by the limited space available. Particular care is necessary in locating the equipment to maintain the proper balance and center of gravity.

equipment. However, the separately-excited shunt motor has been found most desirable because of the simplicity of its control, particularly for the swing and thrust drives, where regenerative braking is required for quick stops and where rapid reversals are necessary. On the hoisting motion the shunt motor permits the empty dipper to be lowered under electric braking with a simple method of control. By using the high voltage inherent in the generator characteristic and by weakening the field, high lowering speeds are obtained. On shovels designed to lower the dipper on a mechanical brake a series motor is most commonly used for the hoist motion, since this motor gives higher overload torque for a given armature current. For the other motions, however, the separately-excited shunt motor is generally favored because of its ease of control.

The armature of the motor and its corresponding generator are connected solidly together, as indicated in Fig. 3, which shows the schematic control diagram of the variable-voltage system with shunt motors. The motor field is excited from a separate source, usually at 125 volts. Provision is made for control of the motor field strength, weakening the field in the *Off* position to reduce heating and in some cases weakening it again on the final points of the controller. As

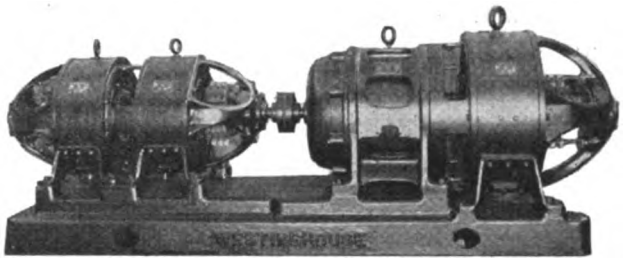

FIG. 5—A FOUR-UNIT, FOUR-BEARING, MOTOR-GENERATING SET FOR A POWER SHOVEL

The arrangement, from the left end, is swing generator, crowd generator, induction motor, and hoist generator. The induction motor is of the squirrel-cage type designed for full-voltage starting. The hoist generator is connected to the motor through an adapter built to facilitate air circulation.

previously mentioned, this assists in obtaining high lowering speed under regenerative braking, when the shunt motor is used on the hoist motion.

The direct-current generators supplying power to the shovel motors are of the differential-compound type, having three separate field windings on each main pole, and sometimes a compensating winding in the main pole face in addition to the regular commutating field pole and winding. Two of the main pole windings are of the shunt type, one separately excited and the other self-excited from the generator armature, the effect of these two windings being normally in the same direction. The third winding is in series with the armature, and is so connected that it opposes the other two when the generator is delivering power to the motor. It is known, accordingly, as the differential-series winding.

Control of the shovel motor is accomplished by reversal and adjustment of the generator voltage, principally by manipulation of the separately-excited field. Since the direction of the motor shunt field remains unchanged, a reversal of the voltage applied to its armature is accompanied by a reversal in direction of rota-

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tion, and with constant motor field strength the speed is almost directly proportional to the voltage. The differential-series winding, being opposed to the other two windings when power is delivered, automatically lowers the generator voltage with a demand for increased current. In the generator the series field is so proportioned that it exactly counterbalances the maximum separately-excited shunt field at the value of current in the motor armature which corresponds to the maximum torque desired. When the current increases to the value which gives maximum torque, the generator voltage is reduced to zero, so that the current and motor torque are limited automatically to a definite maximum value, even though the motor is stalled. The effect of the self-excited generator field is to tend to hold up the generator voltage as the armature current increases, until the desired maximum current is approached, when the voltage falls abruptly.

With the three generator fields properly proportioned the voltage characteristic has the shape shown by Fig. 2, and the speed-torque characteristic of the shunt motor will be of the same form. In comparison with the curve of the steam engine it may be seen that this system possesses the same desirable features,

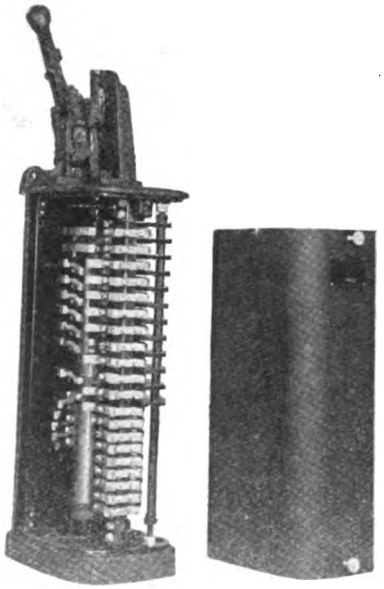

FIG. 6—REVERSING-DRUM CONTROLLER FOR POWER SHOVEL SERVICE

This controller is of the vertical handle type used for hoist and crowd motions. The handle is equipped with ball bearings to permit easy operation. The controller is sturdily built to withstand frequent and rapid operation and the heavy shocks to which it is subjected.

such as automatic limitation of the maximum torque, rapid increase of speed as the load is reduced and high speeds at light loads. Another desirable feature of the system is the fact that when the motor stalls under the maximum torque, the power input to the generator is low for, while the current is at a maximum, the voltage is reduced to nearly zero. This tends to minimize the peak demands on the power system, and as only a small amount of power is wasted in control, the electrical efficiency is comparatively high. It is mainly in this inherent characteristic and the great simplicity of control that the variable voltage equipment as developed for power shovel service proves superior to other forms of electric drive, and has found such extensive application.

The three direct-current generators required in the variable-voltage system are usually combined in a single set and driven by a common motor. With equipments for railroad-type shovels and for the larger size revolving shovel, where ratings are comparatively high and space limitations are not serious, the small direct-current generator necessary for separate excitation is incorporated with the set, making a five-unit layout. Such large sets ordinarily are built in two sections—the exciter, hoist generator and common driving motor mounted on one bedplate and the swing and thrust generators on a second bedplate, with the two sections joined by a flexible coupling. For the medium size revolving shovel (2 to 4 cu. yd.) where compactness of equipment is necessary, the set is generally of the four-unit type, carried on a single bedplate. For the larger sets pedestal-type bearings are generally used, and because the length is limited by the width of the shovel cab, such sets are frequently built with only two bearings, carrying the four machine rotors on a common shaft with the armatures of the swing and thrust generators overhung at opposite ends.

FIG. 7—A FOOT-PEDAL OPERATED CONTROLLER

This is used on the swing motion and is placed between the hoist and crowd controllers so that it is unnecessary for the operator to move his hand from one controller to another. One pedal of this controller is for forward operation of the motor, the other for reverse.

The main driving motor of the set is nearly always an alternating-current machine, since this is the ordinary form of power supply. The practice has been to use squirrel-cage induction motors for the smaller sets and for the large sizes synchronous motors, to secure the benefits of power-factor correction. However, squirrel-cage motors are sometimes preferred for sets of comparatively large rating, because of the somewhat simple construction. Either type of motor can

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be designed for full-voltage starting. This method of starting is usually employed on the smaller equipments.

As operation of motors on the variable voltage system is controlled mainly by adjusting the generator and motor separately-excited fields, the control equipment handles small currents, and it is consequently of simple form. The general practice is to use small drum controllers, such as shown in Fig. 6. Because

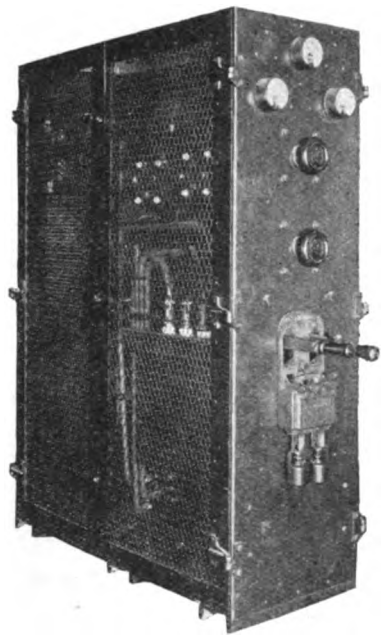

FIG. 8—A STEEL SWITCHBOARD FOR CONTROL OF A SYNCHRONOUS MOTOR GENERATOR SET

This unit is specially built for shovel service. It houses the starting and running circuit-breakers for the synchronous motor, the starting autotransformer, field rheostat and meters.

of the rapid and frequent operations, it is important that the controllers be sturdy, yet light and easily handled. In addition to the main field-control contacts, provision is made for some control of the generator self-excited shunt field, and for operation of brakes and clutches through the medium of magnets or magnet valves. A foot-operated controller as shown in Fig. 7 is frequently used for the swing motion, which simplifies the operators work as it leaves only two handles to be manipulated. Where a dipper trip motor, hoist ram or other auxiliary devices are used, provision is made for controlling them by means of thumb switches in the handles. Resistors used for control of the various fields are of the wire-wound tube type. Present practice is to mount them in a common structural frame provided with a terminal board to which all control leads are connected. This construction facilitates installation and adjustment of wiring.

In many cases the shovel is equipped with a small motor-driven air compressor for operation of air brakes, clutches, etc. For control of these auxiliary devices magnet-operated air valves are used, the magnets being energized by segments of the controller drums or by auxiliary switches. When compressed air equipment is omitted, solenoid brakes are used.

The alternating-current motor driving the main motor-generator set is usually wound for operation at 2200 or 4000 volts, although 440 or 550 volts are frequently used on the smaller equipments. For starting the higher voltage machines, oil circuit breakers are used, generally manually operated. The circuit breaker may be of the separately mounted type, as shown in Fig. 4, or it may be mounted as part of the switchboard. When reduced voltage starting is employed, the combination of starting and running oil circuit breakers is mounted as shown in Fig. 8. For low-voltage equipments the starter is usually a three-pole magnet contactor with the necessary overload and low-voltage protection devices mounted in a steel cabinet, and controlled from a separate push button. Similar starters are used for auxiliary motors driving the exciter set and air compresosr. Such motors are always operated at low voltage, and when the main supply is 2200 or 4000 volts, a bank of special transformers is used.

While the electric shovel has found widest application in mining and similar projects of a more or less permanent nature, it can be economically employed on any work requiring extended time for completion, such as large construction jobs which purchase electric power for various purposes. In most sections power is distributed three phase, 60 cycles so that a shovel

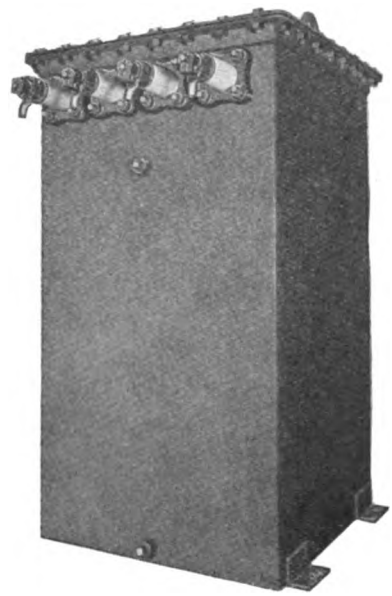

FIG. 9—A SHOVEL-TYPE TRANSFORMER IN A SHEET-METAL TANK

The coils have substantial mechanical bracing to prevent injury from severe vibration and sudden shock due to overloads. As the transformer may be inclined at various angles, the tank and bushings are made absolutely leak-proof, and the core is bolted to the tank.

equipped for operation from such a supply can be used on many different jobs without change. Relatively little change in equipment is necessary to adopt it for use on a power supply of different characteristics. For example, the set shown in Fig. 5 can be used without change on either a 60 or a 50-cycle supply, only minor adjustments in the control being necessary. The same generators are used with a 25-cycle supply, a different alternating-current motor being substituted. Therefore, little or no expense for changes is necessary in moving from one job to another.

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# Automatic Switching Equipment for Mining Substations

S. M. DOUGHERTY
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Westinghouse Electric & Mfg. Co.

IN the early history of the automatic substation, it was generally necessary to present to a prospective purchaser convincing arguments regarding the desirability and necessity of such equipment. Frankly, he was skeptical regarding the ability of a few relays and other devices to perform the sometimes complicated switching functions required of an operator in a manually-operated station. At first, only a comparatively few individuals had faith enough in this sort of equipment to give it a trial, but as these pioneering installations continued to give good service, and as others were installed, this skepticism gave way to confidence until today few if any will question the desirability of automatic switching equipment for substation use. Consequently, the prospective purchaser today no longer questions whether he shall buy manual or automatic substation equipment, but rather what type of automatic switching equipment will best suit his individual requirements.

The first automatic mining installation was not made until after several years of automatic operation

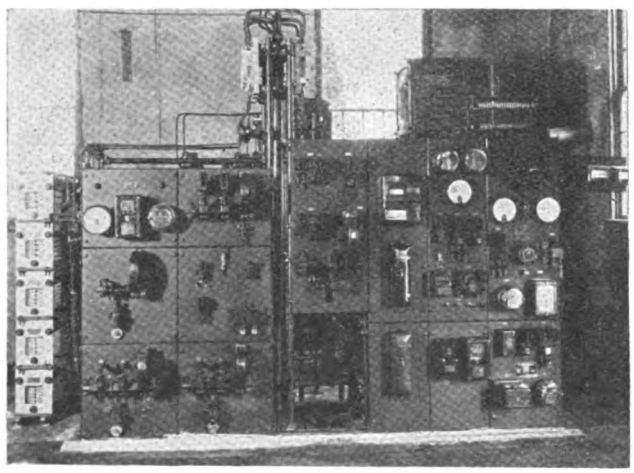

FIG. 1—A SWITCHBOARD IN A FULL AUTOMATIC SUBSTATION
The two panels at the left are for the full automatic control of a mine fan. The panels at the right control a 300 kw synchronous motor-generator set. The starting and stopping of the set is controlled by a time clock shown on the third panel from the right.

in the railway field, but since 1921 the number of units installed per year has steadily increased. This fact alone is sufficient proof that the automatic substation can and does meet an economic demand in the mining industry.

When labor was comparatively cheap there was little reason for installing automatic equipment, because good operators could easily be obtained at reasonable rates. However, the situation was entirely changed when labor costs began to soar. An attempt was then made in some cases to reduce the cost of substation attendance by dividing the operator's responsibility, so that he could perform other duties as well as look after the substation equipment. While this appeared to be a desirable arrangement, it soon developed that the operator was not always present to take care of emergencies promptly. This hampered or stopped production completely until the operator

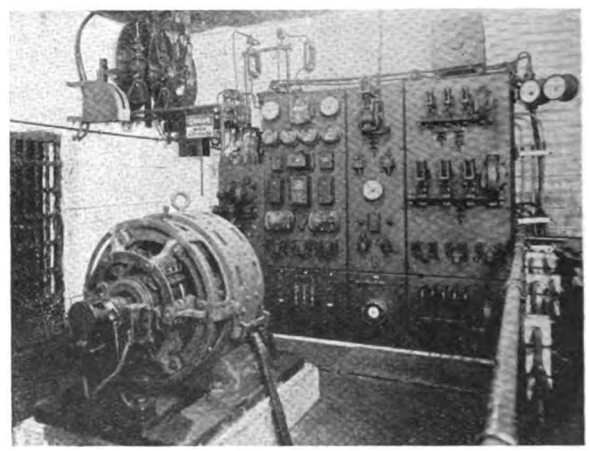

FIG. 2—A SINGLE UNIT AUTOMATIC UNDERGROUND SUBSTATION
Consisting of a 150 kw synchronous converter. The converter is started or stopped by a pushbutton.

could return to the station and restore service. Furthermore, in some cases the repair bills for damage to the substation equipment, occasioned by this type of operation, more than offset the saving in station attendance. Temporary loss of the substation capacity while repairs were being made caused a further loss in revenue. All in all, it is now generally agreed that this method of operation is undesirable and should not be used in mines where the highest efficiency of operation is desired.

It is an altogether different story when automatically-controlled substations are used. Attendance expenses are reduced to a minimum since one man can care for a number of stations. This is possible because a weekly inspection trip to each station is usually sufficient to maintain it in good running condition. There are no unnecessary power interruptions, for the equipment is designed to restore service promptly after short-circuits or overloads which caused the interruption have been cleared. False operations are prevented by a properly designed relay sequence, and full protection against unforseen contingencies is afforded by suitable protective relays which discriminate between

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trouble inside or outside the station and function accordingly.

As in the manual station, there are two general types of conversion equipment available for use in the automatically controlled station, namely, motor-generator sets and synchronous converters. The motor-generator set may be of the induction or synchronous type, although the latter is generally employed because it can be used for power-factor correction. This is very desirable since it is becoming customary for the power company to include a power-factor clause in the contract and considerable savings can be had by improving the power-factor of the connected load. Compound generators or converters adjusted for over-compounding have been used in the past and have been considered essential to maintain proper voltage at the load. Until recently, compound machines were used for the same reason in railway installations, but it has been found that shunt machines give a better over-all performance. There is little doubt that compound machines are desirable and even necessary for a number of mining applications, but there are cases where shunt machines are more desirable. This matter should be given due consideration when substations are located close to one another or where the feeder resistance between stations is low.

No definite statement can be made regarding the choice of either the motor-generator or converter for a given substation, as this will depend to a large extent upon the operating conditions. Approximately 75 percent of the units so far installed are motor-generator sets, and of this number about 85 percent are operating from a 2300 volt line. Of the converter units installed, only about 35 percent are operating at and below 4000 volts. These figures indicate that the motor-generator set is preferred for the lower voltage installations while the converter is used most extensively at and above 6600 volts. The cost of a motor-generator set with automatic switching equipment is less than the same size converter equipment with automatic switching, considered on the basis of either a 2300 or 4000 volt installation. On the other hand, the converter is more efficient than the motor-generator set, usually by about six percent at full load. This difference, if capitalized, may offset the higher initial cost of the converter. For 6600 volts, the difference in first cost favors the converter with automatic switching equipment. When the voltage is so high that step-down transformers are needed for the motor-generator set, then the cost is so much higher that the advantage is decidedly in favor of the converter. A typical switchboard for controlling a motor-generator set is shown in Fig. 1, and in Fig. 2 a general view of the interior of a converter installation.

In the average mine, load conditions are quite variable and usually severe. In the usual installation a locomotive accelerating a heavy load or travelling up grade is likely to demand considerably more than the rated substation capacity. Obviously, the substation unit must be capable of meeting these demands without showing undue distress or flashing. While there is little doubt that the motor-generator set is less sensitive to flashover under severe loads or short-circuits, the modern converter will also give excellent service under these conditions, provided the alternating-current voltage remains fairly constant. This fact is confirmed by the large number of converter units in successful operation in mining installations.

Other factors, such as regulation of the three-phase supply line, space requirements, personal preference of the operating engineers, etc., may have further bearing upon the selection. However, the tendency is to use motor-generators where the alternating-current supply is 4000 volts or lower, because of the lower initial cost and ability to withstand severe overloads and short-circuits. It is not desirable to supply motors of the size used in this service for voltages above 4000, so at and above this voltage the converter is generally selected because it is cheaper and more efficient than the same size motor-generator set with a step-down transformer.

Units ranging in size from 100 to 750 kw are in use in automatically-controlled stations. Of the total

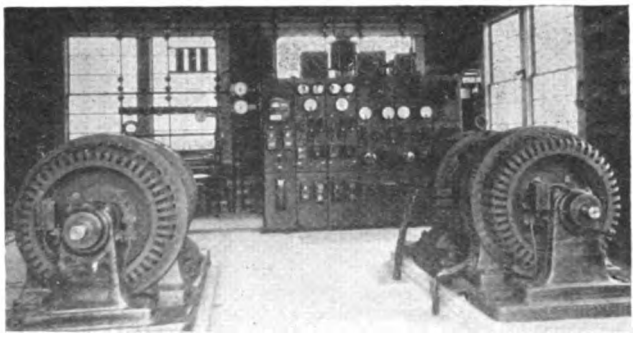

FIG. 3—AUTOMATICALLY-CONTROLLED TWO-UNIT SUBSTATION
The two 100 kw synchronous motor-generators are started and stopped by a time clock. When only one machine is running and a heavy sustained load comes on, the second unit automatically starts, parallels with the first unit and shares the load.

installed capacity, 16 percent is in 150 kw units, 38 percent in 200 kw units, and 32 percent in 300 kw units. These have been considered standard sizes since they meet the requirements of the majority of applications. The direct-current output is distributed throughout the mine usually at 275 volts, although higher voltages have been used.

Single-unit substations located as closely as practicable to the load centers are most desirable. In case there is a highly concentrated load center requiring a large capacity substation it may be desirable to use two units. This makes it possible to effect further economies by shutting one of the units down during periods of light load, and also provides greater assurance of uninterrupted service. However, the majority of units controlled automatically are in single-unit sta-

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tions and there is no doubt but that in most cases such an arrangement is more economical.

Location at the load centers reduces to a minimum the amount of feeder copper required and also greatly reduces the transmission losses. Sufficient consideration is not always given to this last item, for not infrequently cases are found where the mining activities have been extended to such an extent that excessive voltage drop is encountered at the motors. Aside from the losses, this condition also causes motor burnouts, slower speed with consequent lowering of production, excessive maintenance on controllers, and other undesirable operating conditions. In such cases it is usually found that the installation of an automatic substation closer to the load center will soon pay for itself by providing normal voltage at the motors and eliminating excessive line drop and accompanying evils.

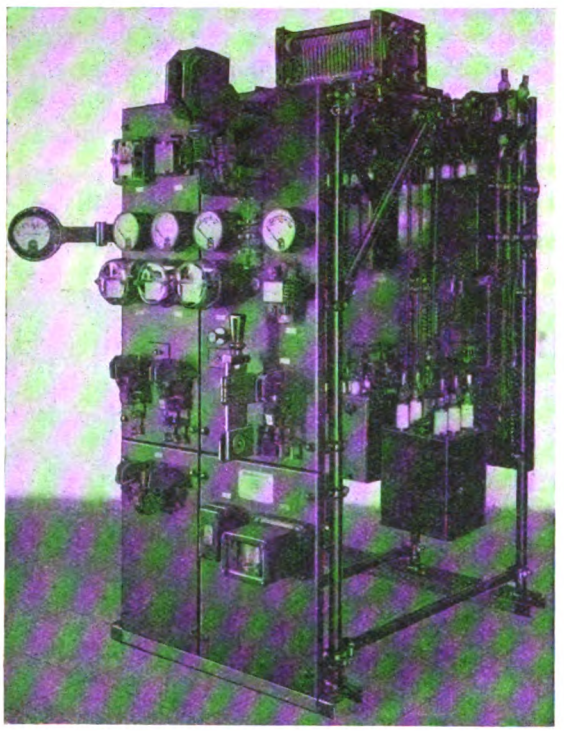

FIG. 4—RELAY AND DIRECT-CURRENT RESTORING PANELS FOR SIMPLIFIED AUTOMATIC MINING EQUIPMENT

A resistance measuring relay is provided for the reclosing of the direct-current restoring contactor. This relay measures the resistance of the feeder or load circuit accurately over wide variations in machine voltage and will not allow the direct-current contactor to reclose until the resistance reaches a safe reclosing value. A time element for the normal reclosure is also provided.

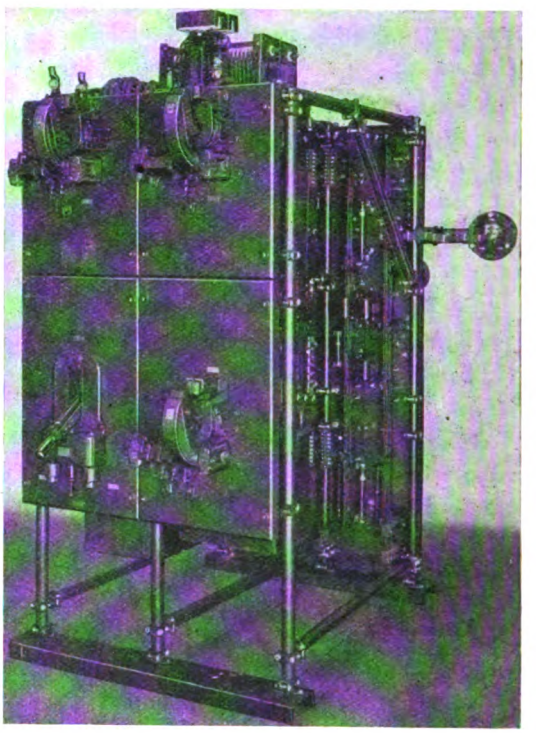

FIG. 5—STARTING AND RUNNING PANELS FOR SIMPLIFIED AUTOMATIC MINING EQUIPMENT

All of the circuits are electrically interlocked so that an operation cannot take place except in the proper sequence. The operation of each relay is dependent upon the successful operation of the preceding relays of the sequence. If a relay should fail to function, the sequence will stop immediately and a timing relay will lock the unit out in case of failure to complete the sequence within a given time.

It is customary to start the station by means of a push button, which may be located either in the station or at some remote point. Other methods of initiating the starting impulse are available, but seldom used. Time clock operation has been employed in some cases where it is desired to have the station start and stop automatically at certain hours of the day. An installation using time-clock control is shown in Fig. 1.

In most cases the starting sequence follows closely the practice in manually-operated stations, and for that reason will not be described here. After the unit has been prepared for connecting to the load, the indication for closing the direct-current line contactor depends upon the type of equipment used. If the unit operates in parallel with others on the system or in the same station, a voltage directional relay is used to prevent closing the direct-current contactor unless the generator voltage is equal to or higher than that of the line. When feeders are used, this is the final check before the machine is connected to the load, but in a station without feeders, a further check is made by the load measuring equipment. Since with this arrangement the generator circuit breaker becomes the feeder circuit breaker also, it is essential that it remain open until the line conditions are such that an overload will not result.

As continuity of service is important, the overload service-restoring type of feeder equipment is used almost exclusively. Upon the occurrence of a short-circuit or overload, the feeder contactor will open and, after a short time delay sufficient to allow the undervoltage release mechanism on the motors throughout the mine to release, the load measuring equipment is connected in the circuit. This device allows the feeder to reclose just as soon as the load resistance rises high enough that an excessive load will not be picked up. This arrangement isolates the defective feeder while allowing the remainder of the system to operate normally. Furthermore, the defective feeder is

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promptly returned to service just as soon as its load conditions are normal, or the short-circuit is removed.

In large well developed mines, it is sometimes desirable to sectionalize tie feeders between stations in such a way that faults occurring at any part of the system will be isolated with the least possible interruption to service. Sectionalizing contactors for this type of service are usually mounted in a weather-proof box and located at the desired sectionalizing points throughout the mine.

Ordinarily the mine electrician or maintenance man does not find it difficult to care for an automatic substation. This type of equipment has been designed to be as simple and rugged as possible, and still provide full protection to the equipment. The number of relays and devices has been reduced to a minimum and the maintenance man soon learns what is required to keep the station in working order. However, in order to meet a definite demand there has been placed on the market a simplified automatic switching equipment which, as its name implies, is less complicated than the standard line. The regular complement of protective features has been retained, but the method of accomplishing the switching functions has been simplified. Even with a limited knowledge of automatic equipment the ordinary mine electrician has little difficulty installing this equipment and placing it in service, as it is a very compact unit requiring a minimum of external wiring and connections. Front and rear views of such a unit for controlling a motor-generator set are shown in Figs. 4 and 5.

Occasionally there are cases where a substation is so located that an operator or other competent attendant is in the vicinity of the station most of the time, but is called away at intervals to perform other duties; or a manual station may be so located that while it is relatively unimportant, it is necessary to retain operators. In such cases, it is sometimes felt that the expense of full automatic operation is not justified, but still it is desirable to take advantage of some features of such operation. Partial automatic equipment is available for such installations. The unit is started manually and left running with a limited number of protective features. Service restoring equipment is used on the direct-current end, and in the event of overload or short-circuit the direct-current machine contactor opens and does not reclose again until the trouble is cleared. However, if some emergency arises, the unit is shut down and remains out of service until the operator visits the station and places it in service again.

Most of the above described features are incorporated in standard equipment, but it is possible to secure apparatus to meet any desired arrangement. The standard lines are designed to meet the requirements of the majority of cases, and unquestionably it is more economical to use standard equipment whenever possible. On the other hand if, after due consideration, it is found that special requirements must be met, these can generally be cared for by modifications of the standard equipment.

# Cost Reductions by Labor-Saving Devices

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DURING the war, industry was engaged in producing a maximum output with little regard to cost. Since the war a highly competitive market has developed, and it has been extremely difficult to operate at a profit. Not all industries have been affected to the same degree, but the coal mining industry is confronted with one of the most difficult problems of all.

Regardless of the particular industry, all seem to be in a declining price market, which is a difficult one for the manufacturer. This is illustrated in Fig. 1, which is a composite price of steel products. It will be noted that this average price for each successive year becomes lower. The problem of the manufacturer is to introduce machinery and new methods which will enable them to manufacture their product at a corresponding reduction in cost. If their costs are not being reduced, but remain constant, their values would be represented by a horizontal line which in time would permit the declining price curve to gravitate below the horizontal cost curve. The steel industry has met this declining cost by electrification, introducing new methods of manufacture, automatic machinery, and by effecting a large reduction in labor. With the old

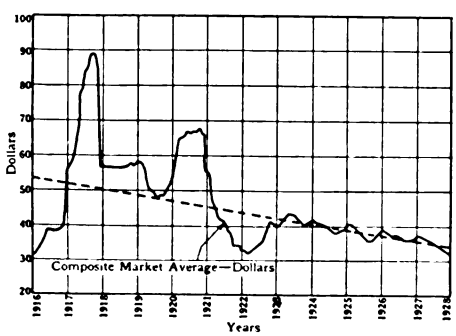


FIG. 1—COMBINED AVERAGE MONTHLY PRICE OF FOURTEEN IRON AND STEEL PRODUCTS

method of driving the units with steam engines many of these new processes and labor saving devices were impossible, but with the advent of cheap electrical power it has been possible for them to select motors

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and control designed with characteristics particularly suitable for the individual applications on which they are used. Fortunately electrical apparatus can be designed with widely varying characteristics, so that it is possible to meet any practical requirement.

When electrical apparatus was first used to replace steam drive it was selected because the power costs were less with electric drive than with steam-

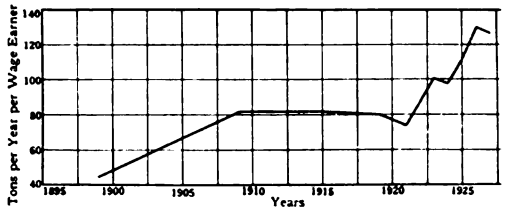


FIG. 2—INGOT TONNAGE PER YEAR PER WAGE EARNER FOR STEEL MILLS AND ROLLING MILLS

engine drive. In many industries today electrification has advanced to a point where this electrical apparatus is used to accomplish substantial reductions in manufacturing costs, due to the fact that labor saving devices can be utilized, and the output increased with the same amount of machinery.

Again referring to the steel industry, Fig. 2 gives the tonnage output per man per year. It will be noted that this has been increased 56 percent over a period of eight years, from 1919 to 1927. Fig. 3 is a corresponding curve which shows the average tonnage of anthracite and bituminous coal mined per man per day worked. It will be noted that the output of bituminous coal per man has increased 13 percent from 1919 to 1927. Since 1924 there has been a slight decrease. In the anthracite field this output per man per day worked has actually dropped 13 percent. This comparison has purposely been made over the period

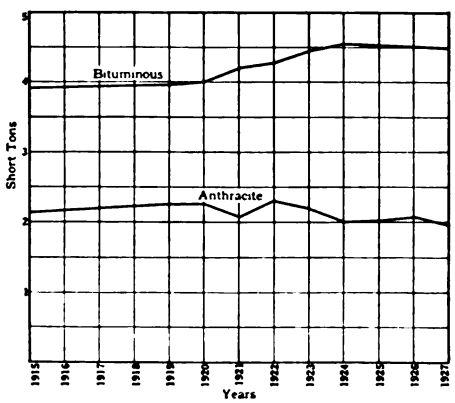


FIG. 3—AVERAGE TONNAGE PER WAGE EARNER PER DAY FOR BITUMINOUS AND ANTHRACITE COAL MINES

from 1919 to 1927, as this is the time when all industrial companies should have been intensely interested in effecting cost reductions by the use of labor-saving devices.

It is natural to expect that the output per man, whether it be coal or steel, will be influenced somewhat by the total annual output; that is, during the years when there is a large demand the output per man would increase and conversely during the lean years the output per man would not be so great. This effect can be seen by comparing Figs. 2 and 4, particularly after 1919. When the tonnage output of steel was small, such as in 1921, Fig. 4, the tonnage output per wage earner, Fig. 2, was low. During 1923, when the

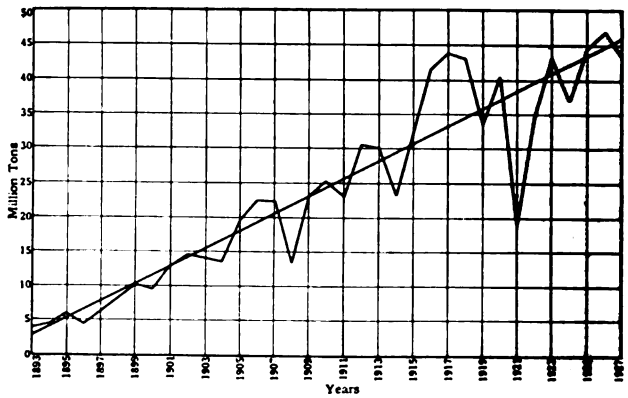


FIG. 4—PRODUCTION OF STEEL INGOTS IN THE UNITED STATES

total tonnage output of steel was large, the output per wage earner was high.

A similar comparison made on coal from Figs. 3 and 5 does not indicate such a variation. The tonnage per day per wage earner seems to be more or less a constant value regardless of varying market conditions. Although the introduction of machinery in the bituminous field, starting in 1920, shows its effect, it is apparent that the steel industry has been more effective in cost reduction by mechanization, regardless of whether they are experiencing a good year or a lean one, than the coal mining industry.

Cheap electrical power has made available one of the greatest opportunities ever introduced into the in-

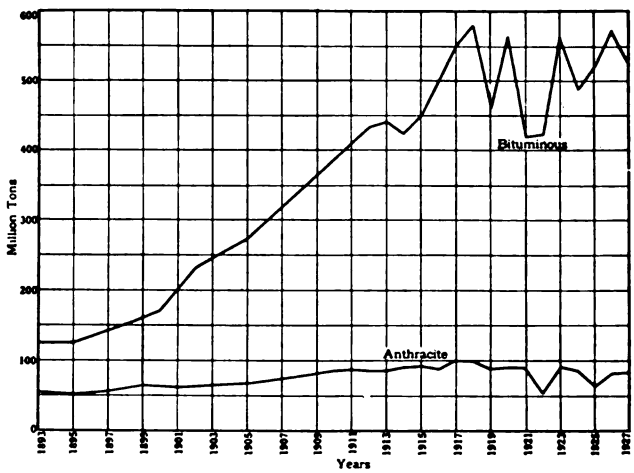


FIG. 5—PRODUCTION OF COAL IN THE UNITED STATES

dustrial field. Its possibilities should be analyzed and advantage taken of every opportunity to reduce costs by its use. Its greatest advantage is not developed by a comparison of power costs between electrically-driven machinery and steam-engine driven apparatus, but in its application to reduce labor and increase tonnage output from a given mine with comparatively little change in investment.

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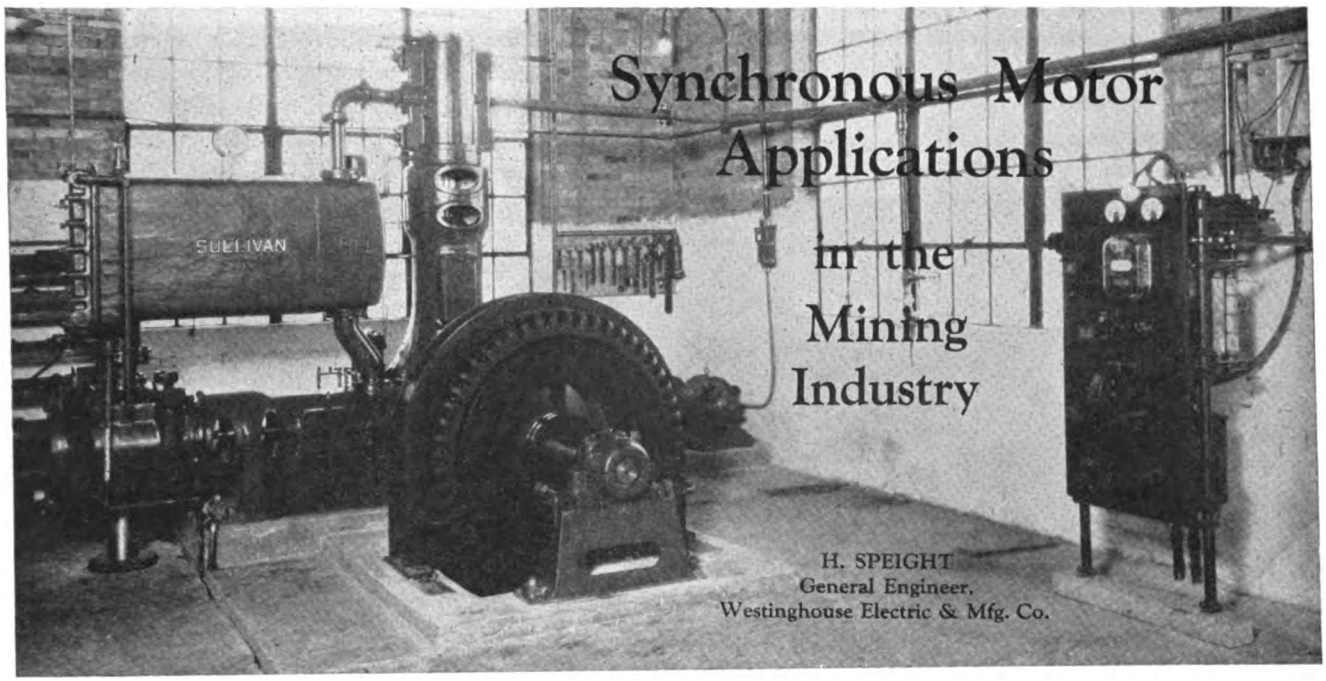


# Synchronous Motor Applications in the Mining Industry

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Westinghouse Electric & Mfg. Co.

THE power-factor of the system at mining properties should be given thorough consideration. Lagging power-factor caused by induction apparatus, if not kept within reasonable limits, will result in low power-factor, which will mean more generating, transmission and transforming equipment to provide the load current. For example, the regulation of a transformer is approximately one percent at unity power-factor and three percent at 70 percent power-factor. Therefore, low power-factor means poor regulation. Line drop increases with the current and line loss increases as the square of the current. The current required for a line operating at 70 percent power-factor, is 43 percent greater than for a line operating at unity power-factor. The voltage drop therefore, is 43 percent greater while the kilowatt loss will be twice as great.

The mine operator purchasing power will be interested in power-factor because low power-factor will increase the power bill, if a power-factor clause is included in the schedule, as is now customary. A synchronous motor receives its excitation from a direct-current exciter and is, therefore, capable of operating at a predetermined power-factor for corrective purposes, depending upon the amount of excitation.

Among the principal early applications of synchronous motors in the mining industry were on motor-generator sets and as drives for compressors. Later, as the demand for synchronous motors grew they were applied to advantageously to fans, turbo or reciprocating blowers, pumps, rolls and crushers, ball and rod-mill drives.

The application of the synchronous motor-generator set in the mining field is to supply the direct current for trolley haulage and gathering locomotive at the mines and smelters and for crane operation at concentrator or smelter. When a synchronous motor-generator set is installed at a small mine, the use of an 80 percent power-factor machine will often supply sufficient corrective kv-a to keep the average power-factor at the mine at approximately 85 percent.

The installation of the synchronous motor for compressor drive is one of the oldest mining applications. The majority of modern synchronous motors for compressor drive are unity power-factor machines, with the motor mounted as shown in Fig. 1, or on the same shaft between the two cranks of a duplex machine. The varying torque of the reciprocating compressor tends to produce hunting, and a flywheel is installed to prevent this, so that the current variation will produce no objectionable effect in the power system. As hunting depends on the motor characteristics, the motor manufacturer should recommend the $WR^2$ value necessary to reduce hunting, or supply constants to the compressor builder. The exciter for a synchronous motor driving a compressor is usually belt-driven from the main drive shaft.

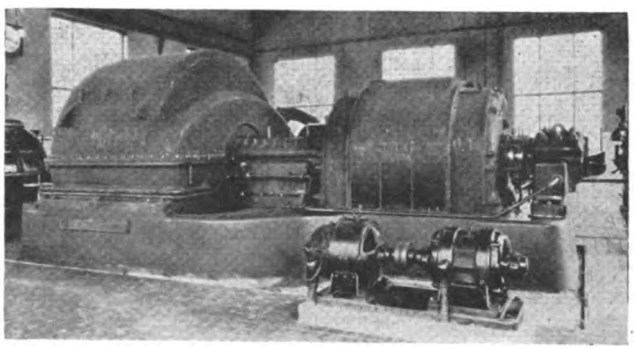

FIG. 1—A 60 000 CU. FT. TURBOBLOWER DRIVEN BY 2500 HP SYNCHRONOUS MOTOR

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The reciprocating compressor, driven by a synchronous motor, can be furnished with control that will function to load and unload the compressor automatically on the setting of a pressure regulator, and the complete installation can be protected during operation by the addition of special features. In case any part of the equipment fails to operate correctly, the machine will shut down, be locked out and an alarm rung.

It is possible to build synchronous motors with high pull-in torques that are capable of starting large mine fans and pulling them into step, but a better method is first to start the motor and have the motor running idle without the load and then attach the fan. This can be done by the use of a clutch-type synchronous motor as shown in Fig. 3. The clutch-type synchronous motor consists of a self-starting rotating field, with the rotor spider free to turn without the shaft, and mechanical connections to the shaft made through the magnetic clutch. When the motor is operating with the clutch unexcited, the rotating field revolves on roller bearings, which are enclosed in a dust-proof housing. All parts of the internal clutch are mounted on a common bedplate with the motor, giving perfect alignment. The clutch-type synchronous motor requires a small motor-generator set or other source of direct current to supply excitation for the motor field and the clutch.

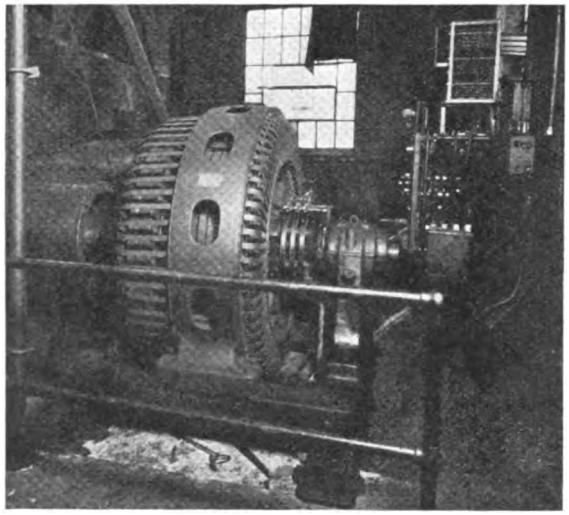

FIG. 3—A 500 HP CLUTCH-TYPE SYNCHRONOUS MOTOR DRIVING A MINE FAN

The mine fan, operating 24 hours a day at constant load, is an ideal drive for a synchronous motor having the combined duty of mechanical load and power-factor correction. It is possible to maintain a higher average power-factor when the correction is obtained from machines operating under constant load, than when relying solely on the benefit obtainable from synchronous motors operating on intermittent load. Summarizing, the advantages of synchronous motors for mine fan drive are:—

Ease of starting without any peak demands (for clutch type).

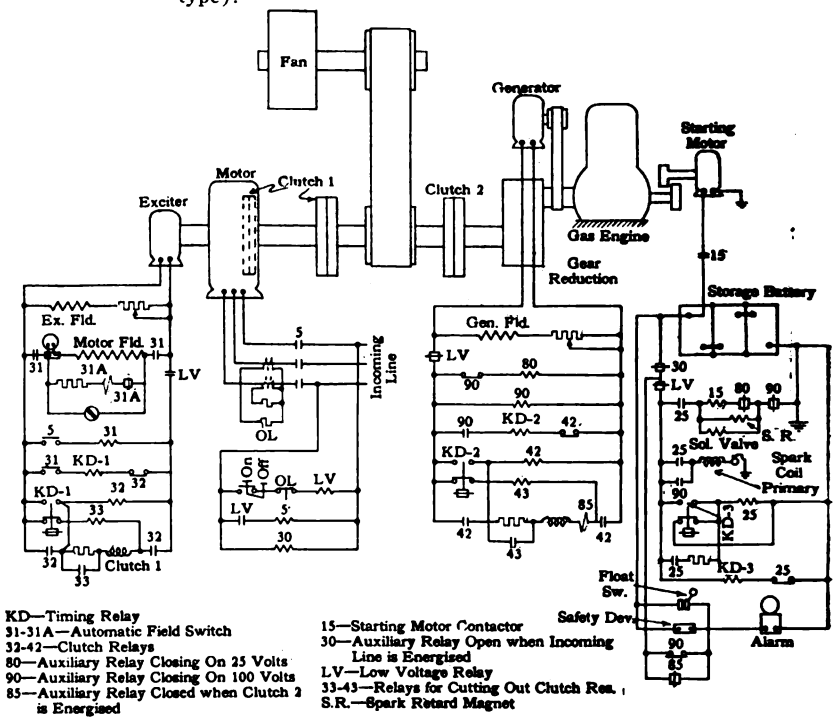


FIG. 2—SCHEMATIC DIAGRAM OF AUTOMATIC CONTROL OF A MINE FAN WITH GAS ENGINE STANDBY

High efficiency.
Improved power-factor.
Ideal location for corrective kv-a without affecting reliability of service.

The control of the clutch-type synchronous motor is simple and can be arranged so that the pressing of one push button will start the motor, bring it up to speed, synchronize it, and then energize the clutch circuit, applying the load.

For gaseous mines where it is necessary for the mine fan to have auxiliary stand-by drive in order to run the fan in case of failure to the power supply, control can be supplied to automatically start the stand-by equipment. In case of power failure to the motor driving the fan, the control will start the gas engine, bring it up to speed, energize the auxiliary clutch, and maintain the fan running at reduced speed until the power supply is again available for the motor. On return of power the motor will automatically start and again take the load, and the gas engine will be disconnected and shut down. A schematic diagram of this control arrangement is shown in Fig. 2.

The tendency is to install turboblowers to supply 3 to 3.5 lb. air for blast furnace operation and 12 to 16 lb. air for converter operation at a copper smelter, owing to the smaller space requirements and ease of operation. A 50 000 to 60 000 cu. ft., low-pressure blower driven by a 2500 hp synchronous motor is shown in Fig. 1. As the blowers are in 24-hour serv-

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ice, the elimination of lagging power-factor on a unit of this size is very desirable, especially as the total power demand at a smelter is between 60 and 70 percent for air supply.

To eliminate flooding, it is essential to keep water out of the mine. Especially in the anthracite field, where an average of 10 tons of water is pumped for each ton of coal mined, the high efficiency of the synchronous motor will justify its use for continuous duty mine pumps. Synchronous motors for pump application have an average efficiency of 95 to 96 percent. A typical synchronous motor driven mine pump is shown in Fig. 5. The control for a mine pump installation with synchronous motor drive consists of a standard synchronous motor starting panel, Fig. 6, and an auxiliary panel to arrange the priming cycle, interlocking the control with the various pieces of equipment necessary for automatic pumping. The auxiliary panel consists of a sequence drum, Fig. 5, and a small interlocking contactor panel, Fig. 7, to give three attempts at priming within a certain period of time. The automatic control of mine pumps will perform the following functions:—

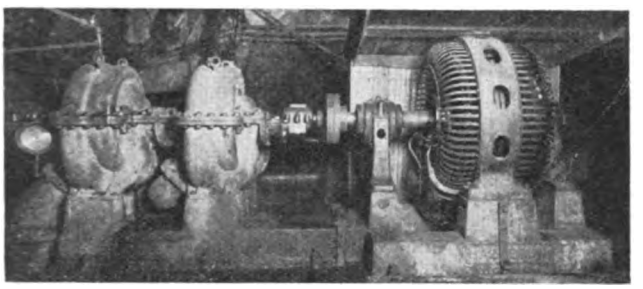

FIG. 4—A CENTRIFUGAL MINE PUMP WITH SYNCHRONOUS MOTOR DRIVE

Start the pump at high water level.
Stop the pump at low water level.
Go through the priming process in starting.
Allow a definite period for priming, if the pump is not primed, shut down all equipment for a definite time interval, permit three attempts at priming, and if the pump is not primed, lock out the equipment and ring the alarm.
Providing pump is primed in any of three attempts, the sequence drum returns to the off position, in readiness for the next starting cycle.

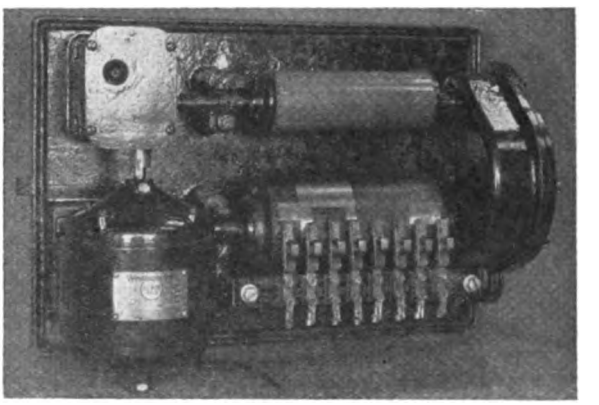

FIG. 5—A SEQUENCE DRUM FOR TIMING THE PRIMING PERIODS OF AN AUTOMATICALLY-CONTROLLED MINE PUMP

When the pump is in operation the equipment is protected against damage through air leaks, loss of water, blocked intake pipe, overheated bearings, loss of pressure or broken discharge column. Should the equipment be shut down from any of the above causes, the control is locked out and an alarm rung.

The special synchronous motor applications in a concentrator are driving rolls and crushers in the crushing plant, and in the grinding department to drive ball or rod mills. In some mills, where the pneumatic-type flotation cell is used, a synchronous motor is used to drive the turboblower supplying five-lb. air for the flotation cell.

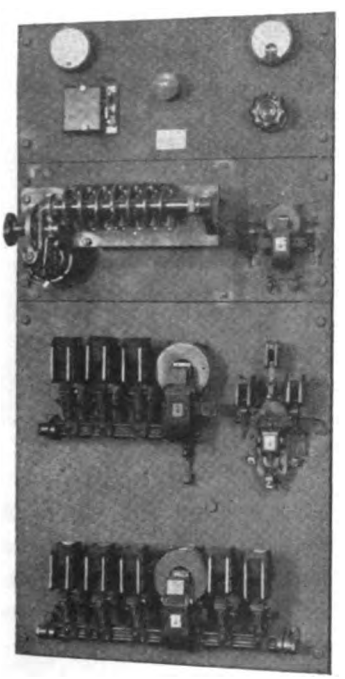

FIG. 6—A STANDARD CONTROL PANEL FOR REDUCED VOLTAGE STARTING OF A SYNCHRONOUS MOTOR

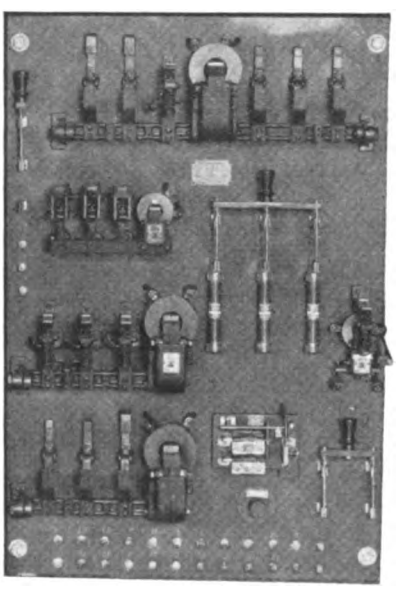

FIG. 7—AN AUXILIARY CONTROL PANEL FOR USE WITH AUTOMATIC CONTROL OF MINE PUMPS

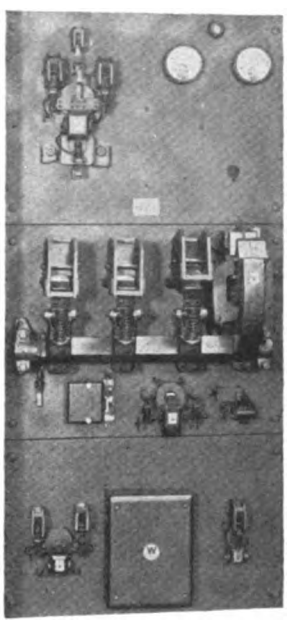

FIG. 8—CONTROL PANEL FOR SYNCHRONOUS MOTOR SHOWN IN FIG. 9

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The motor applications in the crushing and grinding departments call for a motor having a high starting torque, of the value 2.25 times full-load torque. The clutch-type synchronous motor with an oversize clutch has been applied for driving 72 in. rolls equipped with a flywheel.

Motors for these applications are usually slow or

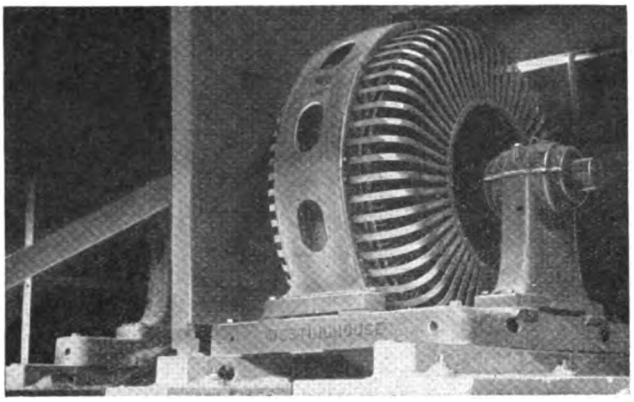

FIG. 9—A 275 HP CLUTCH-TYPE SYNCHRONOUS MOTOR DRIVING 72 IN. GARFIELD ROLLS

medium speed machines, and can be given across-the-line type start. The motor will be started and synchronized on the line before application of the clutch field. When the clutch is energized, the load will be evenly accelerated without resistance in the clutch circuit, providing the acceleration peak is not objectionable. The inherent lag in building the excitation in the clutch field often gives sufficient time for the equipment being accelerated to come to speed with practically no peak load condition. This is shown in Fig. 10, which illustrates the starting of a tube mill when the clutch was energized without any starting resistance in series. For the roll drive mentioned the clutch setting is below the pull-out of the motor, so for instantaneous peak loads, the clutch will slip momentarily, allowing the flywheel to give up its stored energy, and the motor will stay in synchronism, retaining the normal load.

A 275 hp clutch-type synchronous motor driving a 72 in. roll at one of the large modern copper plants is shown in Fig. 9. The control for this application is simple, as shown in Fig. 8. The control consists of an across-the-line type starter, field contactor, clutch contactor, and one resistance point to short-circuit the resistance in series with the clutch. The operation of this contactor is governed by a time relay which is

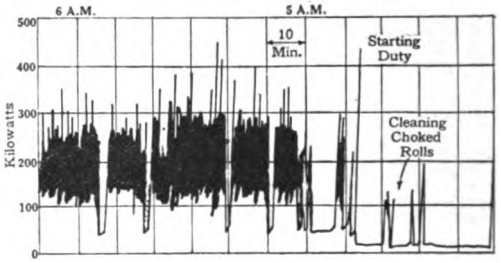


FIG. 11—SECTION OF DAILY LOAD CHART OF MOTOR SHOWN IN FIG. 9

adjusted to suit local conditions. The load on the rolls is shown by Fig. 11.

For ball and rod mill drives, where a motor having high starting torque characteristics is necessary, the synchronous motor is often applied. Another application for synchronous motors is driving the blower fan, used for supplying air to the roasting pans of the Greenwalt or Dwight Lloyd type of sintering plants.

The synchronous motor is excellently adapted to the above applications because of its high power-factor, high efficiency and reliability in service. The operating time of many of the applications is practically continuous, and the remainder will average eight hours per day, so that in those cases where the synchronous motor is higher in first cost, the lower power rate for a high power-factor load will usually compensate for the additional capital outlay.

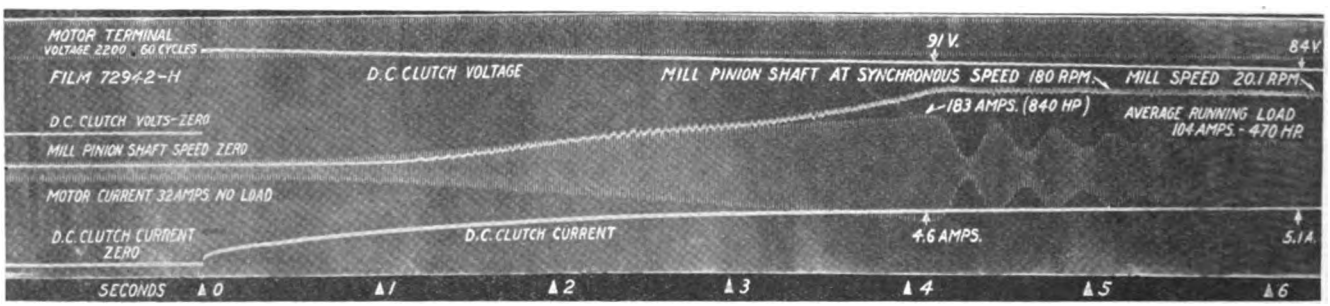


FIG. 10—AN OSCILLOGRAM SHOWING LOAD CONDITIONS DURING THE STARTING OF A TUBE MILL

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# A Theory of Lightning

CHARLES LeG. FORTESCUE
Consulting Transmission Engineer,
Westinghouse Electric & Mfg. Co.

Lightning is of great interest to all engineers operating transmission lines which cover a wide territory. The general conclusions arrived at by the klydonograph studies that have been carried out during the past three or four years are: (1) Surges due to switching and other operations are of negligible importance, and very rarely cause other disturbances or result in breakdown of apparatus. (2) The surges that do cause trouble, such as spillover of insulators or failure of apparatus, and which are likely to result in serious outages, are all caused by lightning.

THE theory of lightning is a subject which is naturally approached with a good deal of trepidation. While the phenomena are extremely vivid and, from the standpoint of the ordinary observer, awe-inspiring and many times of great grandeur, from the point of view of the scientific observer, they are somewhat intangible. Observations are difficult to make. The subject still is, and will be for some time, in the stage where it is a problem for the physicist. The engineer usually has the duty of interpreting the work of the physicist into practical values; but in this case the necessity for remedial measures requires that the engineer take what the physicist has found, and supplement it with such experimental work as he is able to carry out.

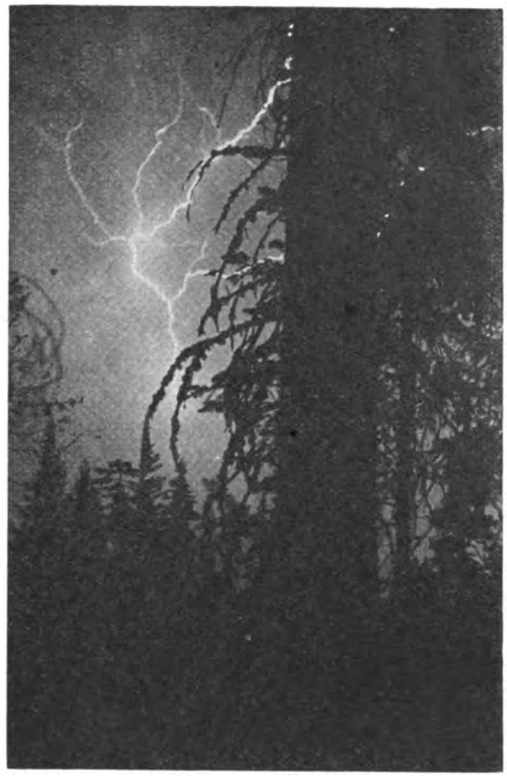

FIG. 1—LIGHTNING IN THE SIERRAS

### FORMATION OF A THUNDER CLOUD

The principal investigators in this field are Simpson, Wilson and Norinder. They have carried on very important studies and have contributed very valuable work in the theory of lightning production. Simpson has, I think, explained in a satisfactory manner, the cause for the enormous charges appearing in thunderclouds. His theory is as follows: Thunderclouds are of the type known as cumulus. Cumulus clouds by their formation show that the atmosphere in which they appear is in a state of turmoil. The wind striking the front of the cloud takes an upward direction, and in doing so breaks up the raindrops formed by the condensation of the moisture. Negative charges are thereby released from the raindrops so that this region of the cloud becomes positively charged. The negative charges and the finely divided spray formed by the wind striking the raindrops are carried by the wind into the body of the cloud which thereby becomes negatively charged. Simpson has shown that, with raindrops of 0.5 cm. diameter, which is the largest size drop that can exist and be stable, and with a wind having a vertical component velocity of eight meters per second, raindrops of this diameter will remain suspended. As a consequence the positively charged region contains water in the form of large raindrops which are highly charged with positive electricity. This charge may be removed, (1) by a direct discharge between this region and the cloud itself or another cloud, (2) by a direct discharge to earth, (3) by the rain carrying the charge direct to earth.

A reproduction of an illustration in the paper by Simpson is shown in Fig. 2. The full lines show the direction of the lines of the air. The vertical dotted lines show the direction in which the rain may fall. As may be seen, at the edge of a positive region the direction of the stream lines may be such as to permit the formation of rain. Thus, the region may be discharged by the fall of rain at the same time that it is continuously being charged by the formation of raindrops, and condensation at the other edge of the positive region.

There is a strong probability that the positive region may be discharged very slowly, by diffusion to the earth through the escape of positively charged raindrops, or condensed vapor, at the lower part of the positive region, and this may take place without the formation of rain.

Simpson has shown quite conclusively that both positively charged rain and negatively charged rain may be formed from thunderclouds, but the positively charged rain carries much more electricity than that negatively charged. Evidence shows that the fine, thin, misty rain may be negatively charged; the heavy down-

*Revised from a talk before the Cincinnati Section, A.I.E.E., Nov. 16, 1927.

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pour is usually positively charged.

A fact brought out by these scientific investigators, perhaps not realized by the ordinary observer, is that the volume included in these phenomena may be very large, and the charged part of the cloud may extend up, being limited only by the region known as the stratosphere, or the portion of the atmosphere where the temperature becomes independent of altitude. The height of this stratosphere, or isothermal region, depends upon season, upon latitude and other conditions, and may be four miles. However, the highly charged portion of the cloud is probably very much closer to earth, as the negatively charged vapor is carried by the wind into the upper cool region, where it is condensed into a cloud and settles down, by the combined effect of gravity and wind, into a heavy cloud mass in close proximity to the earth, the height of the center of the charged area probably being of the order of 1 to 2 miles.

Dr. Norinder, Peek and other observers, have shown that the static gradient due to a thundercloud

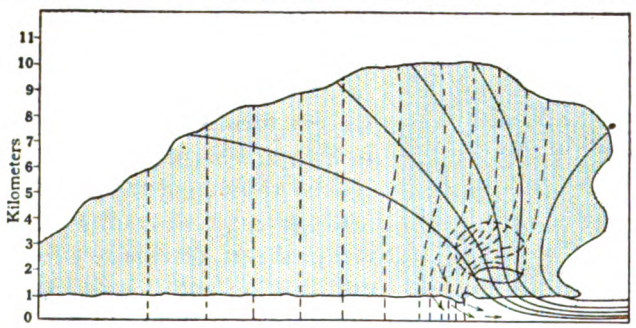


FIG. 2—A REPRESENTATION OF AN ELECTRICALLY CHARGED CLOUD

is of the order of 50 000 to 100 000 volts per foot. Computations based on these gradients indicate that the thundercloud may have a charge of the order of 6 to 10 coulombs, depending upon the size and height of the cloud. The potentials to which the cloud is raised, based on the same data, appear to be of the order of 130 000 000 volts.

The calculations based on the gradients observed, indicate very much smaller charges than those arrived at by Simpson. However, Simpson includes in his computations the whole region that contains negative charges. The actual portion of the cloud which is most active in producing the gradient probably will be relatively small in volume and, while densely charged, will carry a much smaller total charge. Moreover, the existing positive region in the thundercloud will neutralize a large part of the upper cloud which is negatively charged.

## MECHANISM OF LIGHTNING[1]

The phenomena just described indicate that lightning strokes may be both positive and negative. However, the positive charge may leak away, without causing lightning, either through the discharge by rain or possibly by diffusion to the negatively charged part of the cloud. Actual gradients caused by the positively charged region probably are not large, on account of the relative position of the negatively charged portion of the cloud with respect to this positively charged region. It seems evident from this that the higher potentials will increase negatively from earth to cloud, and that the probabilities are greatly in favor of lightning discharges from the negatively charged clouds.

Simpson infers from experiments which he has carried out, that where a cloud is negatively charged, lightning will start from the earth to the cloud. I am not sure of the conclusiveness of Simpson's experiments. Mr. Torok recently has done some work on arrested discharges between sphere-gaps. Some very beautiful photographs have been taken of these arrested discharges, which show the same phenomena that Simpson has observed with respect to the streamer forming at the positive electrode, namely, that it is extremely intense, and that at its tip it branches out. But these photographs also show that the same type of phenomenon may, and does, occur at the negative electrode, and in every case the formation first takes place at the electrode having the higher gradient, whether it be positive or negative. I have evolved the following explanation of the mechanism of breakdown between spheres, for which I am to a large extent indebted to Dr. Harris J. Ryan who gave me the clues on which this explanation is based.

When two spheres are subjected to a difference of potential, the electric field set up causes ionization by collision, the result of which is to increase the number of free electrons and charged air molecules in the region surrounding the two spheres. Recombination, of course, is continuously taking place, to more or less extent but a point is reached when the recombinations between positively charged molecules and the free electrons produced by collision become so rapid that ultra violet rays are emitted. This is shown by the fine hazy glow which appears to be more or less stratified and can be photographed in the sphere gap with the quartz lens camera. It may make itself manifest in insulator strings by the corona glow, though this usually cannot be observed in the sphere gap because, at this point, the region between the spheres has reached a critical point and flashover takes place so quickly that the eye usually does not observe the preceding glow. However, by arresting the flashover, which is done by impressing a steep wave front on two sphere gaps and chopping the surge with one before it reaches the flashover point on the other, these phenomena may be observed and the glow due to the emission of ultra violet rays preceding the actual flashover may be observed. When the critical point characterized by this ultra violet glow is reached another phenomenon takes place, usually starting first at the electrode where the gradient is highest, and is characterized by the emission of in-

[1]Since preparing this article I have read a paper written by Marcel A. Lissman on the subject of the lightning flash and find that he has independently arrived at substantially the same ideas on the subject as here presented.

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tense light rays. The explanation of this second phenomenon is that the air molecules become heated by the ultra violet emission, and reach a stage where they become unstable; and the negative charges in the molecules become dissociated, in other words, the molecule is broken up. This is characterized by an intensely luminous glow. This glow or streamer builds out from the electrode at an extremely high velocity. In the case of the sphere gap several streamers are formed simultaneously, and the rate which the formation progresses across the gap is of the order of one-tenth the velocity of light. These streamers shoot out from the sphere gap, starting at the sphere having the highest potential gradient and later forming at the other sphere. When two such streamers meet at some intermediate point of the region the arc takes place and the potential between the spheres is reduced to the arc potential, which is comparatively low. This reduction of potential, however, apparently does not take place until the actual physical coming together of these two streamers.

An understanding of the mechanism of flashover between spheres is important as it gives us some idea of the mechanism of lightning discharge. If we assume that Simpson's theory is correct, and that the streamer always forms at the positive electrode, and on the assumption that the higher gradients are increased negatively from earth to cloud, we conclude that the lightning discharge almost invariably starts at the positively charged earth and branches out into the cloud. Simpson has shown some photographs which seem to bear this out. The arrested discharges, which Mr. Torok has made, seem to indicate that, although negative streamers may form, they do not have the branching effect at the tip which is characteristic of the positive streamers. The advantage of Torok's observations lies in the fact that the phenomena all took place in a very small fraction of a microsecond, so that it was not possible for the branching effect to be the result of subsequent phenomena depending upon the initial streamer.

It is not my purpose here to discuss the phenomena of flashover between spheres. I have merely brought this up for the purpose of throwing light on the discharge between earth and cloud. The phenomena of arrested flashovers has been covered in Mr. Torok's paper[2].

### TIME REQUIRED BY DISCHARGE

We may deduce from the preceding discussion that the discharge between earth and cloud requires a certain length of time. During this time, before the actual discharge takes place, a conducting path is being formed between earth and cloud; the rate at which this path is formed is somewhat in doubt, but it can be safely inferred that the rate of formation is less than that between spheres where the gradient is extremely high, and nearly uniform from sphere to sphere. We may assume, therefore, that the minimum time limit may be based on a velocity of the order of one-tenth that of light, so that the time required to form the conducting path will be of the order of 15 microseconds which is, from the point of view of surge phenomena, comparatively slow. However, the actual time is probably several times this value. This simply sets up the conducting path and does not determine the time of discharge.

Once this conducting path is formed the discharge takes place in exactly the same manner as a surge moving along a conducting path, that is to say, with the velocity of light. Assuming that the distance from the center of the charged area of the cloud to the earth is 2000 ft., the time for any portion of the discharge to reach earth will be of the order of two microseconds. The nature of the surge, however, is that of a charged body containing a relatively large charge, discharging through a relatively constricted path, or high resistance conductor; consequently, the surge will carry charge to the earth until the potential of the portion of the cloud involved is lowered to such a point that the arc cannot be sustained. The lightning flash will then subside. However, if the cloud is highly charged and the region discharged is a relatively small portion of the cloud, it may recover its potential very soon and a second discharge will take place over the same path. This may be repeated several times. This is shown very graphically by certain observations published[3] by Dr. Norinder, one figure of which is reproduced in Fig. 3.

The idea has been emphasized that the discharge of a portion of a cloud is a relatively slow process. If it were not so, the potentials that might be obtained in transmission lines due to a lightning discharge would be very much in excess of those that have been actually observed.

Since the discharge of the cloud is only partial and relatively slow, the induced potentials on transmission lines are usually not very high, and these induced potentials, as shown by the klydonograph, are nearly always positive. From our klydonograph records I have come to the conclusion that the great majority of surges produced by lightning on transmission lines are positive and comparatively low in value. Only rarely is an induced surge high enough to flash over insulators on high tension lines. However, some negative surges have been recorded, and these were always of extremely high value.

### THEORY OF NEGATIVE SURGES

The theory of induced surges does not seem to be sufficient to explain these high negative surges. Furthermore, it does not seem logical to suppose that the theory of probability favors the transmission line over other parts of the earth in regard to lightning discharges. I have therefore come to the conclusion that these observed high negative surges are due to the

[2]Presented at the Midwinter Convention of the A.I.E.E. Feb. 1927, and the discussions thereon.

[3]In the Electrical World in 1924.

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effect of more or less direct lightning strokes to the line. It is generally assumed that a direct stroke of lightning on a transmission line is extremely disastrous, but I cannot find any logical basis for this. We all know that church spires are sometimes struck, and generally very little harm is done. Sometimes a lightning stroke will destroy a spire, and it frequently rips up a tree, but the tree itself is a very poor conductor and, therefore, absorbs a large amount of the energy of the stroke.

A transmission line, on account of its high relative capacity, need not absorb the full energy of the stroke but simply transmits it in the form of a surge. Therefore, if the current density in the surge path of the lightning stroke is not sufficient to fuse the conductors, there is no reason why a direct stroke should not pass into the line and produce a high negative traveling wave. Again, the stroke may not be direct to the line, but may be very close thereto, and in this case a large volume of air is included in the ionized portion of the stroke. This will conduct a comparatively large portion of the negative charge passing down the lightning stroke into the line itself and cause a negative traveling wave. It would be highly interesting if utility engineers in lightning territories would try to obtain information as to the nature of the lightning discharges which cause flashover of insulators, and determine whether there is evidence, such as pitting of conductors, of the direct passage of lightning from the cloud into the transmission system. However, whether such evidence is available or not, I am convinced that many of these high negative traveling waves are caused by more or less direct strokes.

In what way then does such a negative stroke produce a wave in the transmission line? I have stated that the wave discharges along the conducting path formed by the dissociation of air molecules, and the nature of this discharge is the same as a wave along the wire. Consequently, when such a discharge takes place to the transmission line the action is just the same as that of a wave flowing from one transmission line into two transmission lines branching from its extremity. If we know the characteristics of the surge traveling in the first transmission line and the characteristics of all transmission lines, we can calculate approximately the surge that will flow in the two branches. Roughly speaking, the surge flowing in the branched lines will have two-thirds the value of potential of the surge from the first line, and probably this is about the order of the surge in the transmission line resulting from a direct lightning stroke. These theories are new and we have not been able to go far enough to be able to predict from the characteristic of the cloud itself and its potential, the potential of the wave that will flow along the lightning path to the transmission wires. The values from the relative capacity of the portion of the cloud involved and the capacity per unit length of transmission lines, without taking into account the traveling wave, are very much too high. This, of course, is partially due to the fact that when it strikes a transmission line the wave is dynamic, whereas the static wave is based on the actual charge of the portion of cloud, and has twice the potential of the dynamic wave. We hope however, after further study, to be able to arrive at some rough value which will be in accord with observed results.

*(To be Continued)*

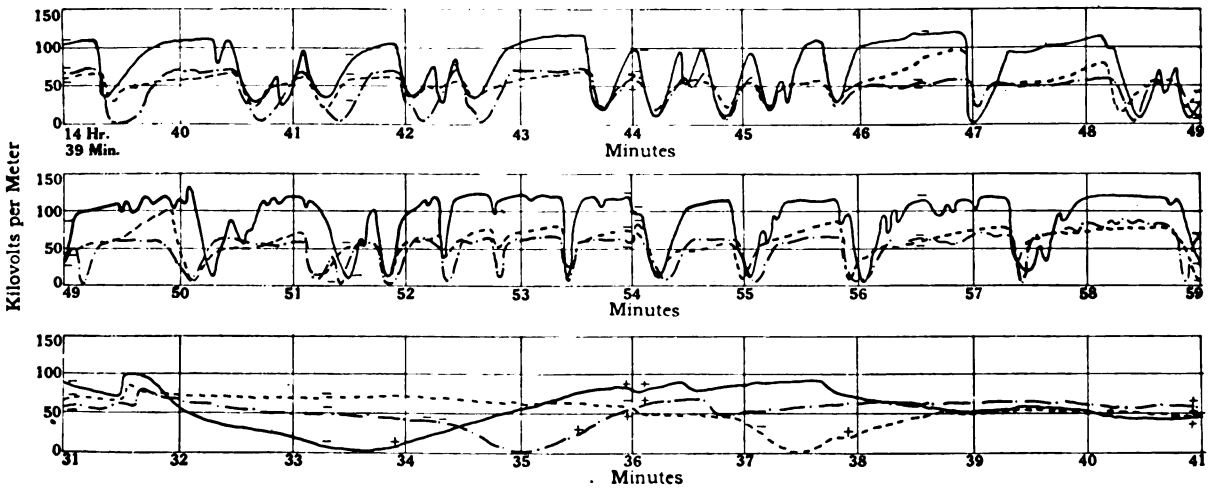


FIG. 3—THUNDERSTORM FIELDS MADE AT STATIONS 1.4 KM TO 2.2 KM APART

Regenerative action in the clouds and a rapid building up of the charge after each charge is shown in the upper two sections. Records, taken half an hour after the storm had subsided, given in the lower section, show a gradient change from negative to positive.

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# Conversion Equipment for Mining Substations

R. E. POWERS
General Engineer,
Westinghouse Electric & Mfg. Co.

IT has been the practice of most mining companies to concentrate all conversion equipment in one or more large substations located at some central point with respect to the different workings, the power being distributed over radial feeders to the various load centers. The substation location was often determined by a number of factors other than engineering. The difficult problem of securing competent and reliable substation attendants, at the prevailing wage, to work in isolated plants was an important factor in determining the policy of centralizing the substation equipment. Centralization reduced the number of operators and also made possible better working and living conditions.

This situation, while satisfying a number of problems outside of engineering considerations, left many features to be desired. It tended to impair service and was responsible for high distribution losses, as well as low voltage at the mine face; it being economically impractical to compensate for excessive line drop by the installation of feeder copper. The effect upon equipment and output, due to low voltage at the mine face, is well known, and its results, although difficult to evaluate, should be given due consideration in a comparison of different systems of operation.

The development of the automatic substation, with the elimination of attendance problems, makes it economically possible to install small conversion units near the load centers to secure high average operating voltage, low distribution losses and economy incident to the operation of automatically controlled non-attended stations. The elimination of the attendance greatly simplifies the problem, and permits the location of the substation at points determined by engineering consideration only.

A better understanding of substation application, relative to selection of equipment and substation location, is shown in the decided tendency toward the installation of numerous single or double-unit automatically controlled substations located at or near load centers. The units comprising mining substations are usually of small capacity, commonly ranging in size from 100 to 300 kw, though occasionally cases may justify 500 to 750 kw capacity.

During a transition period certain problems sometimes assume considerable importance and usually there is a misunderstanding regarding these problems and the methods available to produce a cure for these difficulties.

As a result of the change from the large centralized manually controlled substation, to the small isolated automatic substation, the problem of flashing at the commutator of the conversion equipment has assumed a position of relative importance. Flashing is not a new or recently discovered difficulty, but has been present to a more or less degree in practically all mining substations operating at 550 to 600 volts on the trolley. However, in large manually operated substations flashing difficulties are not so common. The large number of units on the bus at one time, although it increases the total short-circuit current delivered over a given feeder due to a fault on the trolley system, reduces the fault current per generator, and in many cases this value is low enough to prevent flashing. Moreover, when a flash does occur, the operator is available immediately to sandpaper or stone the commutator and put the unit back into service with a minimum delay. This condition of operation, although objectionable, does not influence mine output seriously and, therefore, has not become an issue.

In an automatic installation, relays are provided that function to disconnect the conversion unit from the line and lock-out the switching equipment, so that the unit cannot be restarted automatically until an inspector visits the station, makes the necessary repair, and manually resets the lock-out features. The use of the automatic switching equipment permits the location of the substation at or near the load center to secure the benefits of low line losses and high operating voltage at the mine face. The proper location of the substation with respect to the load center, in many cases, places the substation physically in localities that are often difficult to reach promptly, so that a lock-out of the substation equipment due to a flash over is serious. To locate an inspector and have him reach the substation to inspect and repair the equipment, preparatory to placing the unit back into service, often requires an hour or more. During this time the electrical equipment in the mine supplied by this station is idle, with consequent decrease in tonnage output for the shift.

To produce a satisfactory automatic substation, the conversion equipment in that substation must be free from flashing due to faults on the trolley system. The general conditions existing within the mine itself are such as to cause frequent short-circuits between the trolley and rail. A large number of faults are caused by slate falls, grounding of electrical equipment, gathering locomotives running over their supply cables, and numerous other contingencies well known to the operating engineer. In manually controlled stations, flashing has been looked upon as a necessary evil,

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whereas in automatically controlled stations, the period of outage incident to a station lock-out has made it necessary to secure a unit that is free from flashing.

### CAUSES OF FLASHING

Satisfactory results have been secured in the 250-275 volt field with standard machines and switching, whereas in the 550-600 volt field, difficulty has been encountered in a number of cases with standard industrial substation equipment; hence this article will deal entirely with units and switching designed for operation on 600 volt systems. The synchronous motor-generator set has proven to be the most popular type of conversion apparatus in the mining field, and it is felt that a general discussion of flashing on direct-current generators and the changes in machine design and switching that have been brought about to eliminate flashing due to short-circuits between trolley and rail will be of benefit to those interested in this particular problem.

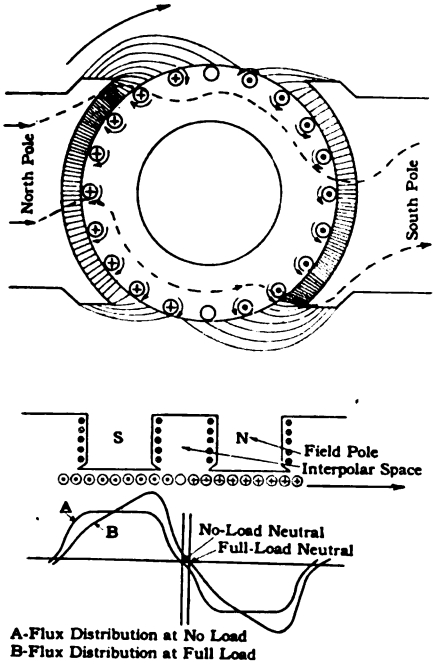


FIG. 1—AIR-GAP FLUX DISTRIBUTION OF A TWO-POLE GENERATOR

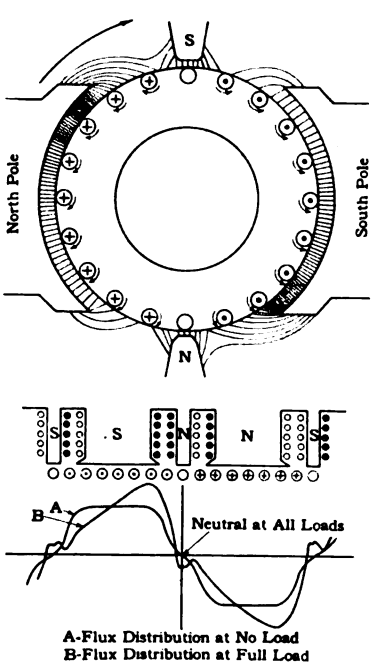


FIG. 2—AIR-GAP FLUX DISTRIBUTION OF A COMMUTATING-POLE GENERATOR

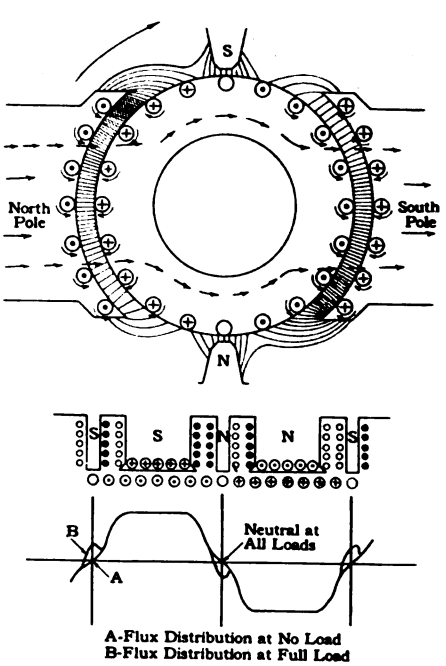


FIG. 3—AIR-GAP FLUX DISTRIBUTION OF A COMPENSATED GENERATOR

Flashing at the commutator due to short-circuits is caused by the inability of the ordinary shunt or compound generator to commutate the excessive current encountered. In the standard commutating-pole generator the flow of short-circuit current through the armature distorts the field form in such a manner as to crowd the main field flux toward the trailing pole tip, thus causing a high voltage to be induced between commutator bars directly ahead of the brushes, as shown in Figs. 1 and 2. In the commutating-pole generator, armature current is carried by the commutating-pole winding to produce the resultant flux in the interpolar space required to secure satisfactory commutation.

It is well known that the commutating-pole magnetic circuit saturates at heavy overloads of short-circuit nature, thus upsetting the relations in the commutating zone. Under such conditions, heavy local currents will flow in the coils short-circuited by the brushes, and the direction of current flow will be such as to be detrimental to the best commutation. This local current will add to the load current at the toe and subtract from the load current at the heel of the brush. This produces an unequal current distribution across the brush with consequent local heating. There may be a large arc or flash from the front edge of the brush, due to heating particles of the carbon brush to incandescence or the vaporization of copper, that forms an excellent conducting medium between bars. Or a flash may be started between two adjacent bars at some point between brush arms due to abnormally high voltage between these bars, caused primarily by field distortion. This flash may be carried around the commutator due to its rotation. Regardless of the initial action starting the formation of an arc, the flash itself is caused by the vaporization of conducting materials. If the heat developed incident to the formation of the original arc is sufficient to vaporize additional conducting material the arc will grow and continue until a complete buck-over results. In very small machines an arc between bars may occur without leaving evidence, whereas in large machines with low-resistance conductors, an arc usually melts out small craters at the edges of the bars and the vaporized material may cause spreading of the arc until it assumes the proportion of a flash over between brush arms.

### THE PREVENTION OF FLASHING

From the above considerations it is apparent that flashing is a function of both the magnitude and duration of the short-circuit current. Experience and tests

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have clearly shown that the length of time that the fault current is allowed to flow has considerable effect upon the flashing of a generator. The higher the short-circuit current, the shorter will be the period of time during which the opening of any circuit interrupting device will prevent flash over, and conversely, the longer the period of time required by the opening of the circuit breaker, the lower the value of fault current must be in order that flash over will not occur. As flashing depends upon both the magnitude and duration of the fault, two commercial methods are available for protecting direct-current generators from flashing.

1—The first method, and the one most generally employed, is the use of the feeder system as a cushioning resistance to limit the fault current to a value that can be successfully commutated by the generator during the period required for the opening of the average carbon circuit breaker or contactor.

2—The second method uses protective equipment in the form of high-speed, direct-current circuit breakers, that interrupt the fault current before flash over can occur.

Each of the methods mentioned in the preceding paragraphs for machine protection has its field of application, and due consideration should be given to all factors involved before a decision is reached to use one system in preference to the other.

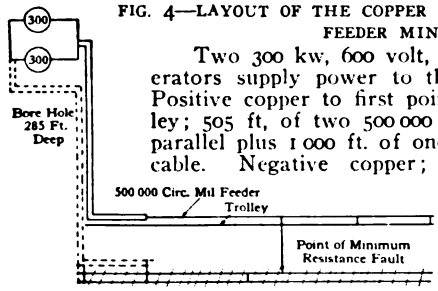


FIG. 4—LAYOUT OF THE COPPER IN A LOW-RESISTANCE FEEDER MINE

Two 300 kw, 600 volt, compensated generators supply power to the trolley system. Positive copper to first point tapped to trolley; 505 ft, of two 500 000 circ. mil cable in parallel plus 1 000 ft. of one 500 000 circ. mil cable. Negative copper; 505 ft. of two 500 000 circ. mil cables in parallel; 80 lb. rails well bonded. Loop resistance (positive and negative) to first point tapped to trolley = 0.0379 ohms. The units have been in operation for over a year on this low resistance network, protected only by a standard slow speed contactor, without a single flashover.

SERIES RESISTANCE

The use of the inherent resistance of the feeder system itself as a means of limiting the fault current to a value that can be commutated successfully during the period required to open an ordinary carbon breaker or contactor has proven to be quite effective as a means of preventing flash over.

The general layout of the trolley and feeder system in the modern mine is such that the feeder system may be used readily to secure the necessary cushioning resistance without additional expense or increasing the losses in the feeder system. In the average underground distribution system the power is carried to the mine face through radial feeders. In many cases they are brought underground through an abandoned shaft or a bore hole. The method used in laying cables is ordinarily good, and the possibility of faults occurring on main feeders is remote. The use of the inherent resistance in the feeder circuits as a means of securing short-circuit protection in no way penalizes the system operation from a loss or voltage standpoint, as the feeder circuit is essential to satisfactory operation, and must be supplied regardless of the protective measures used. In the average mine the bulk of power is taken from the trolley at a distance remote from the point first tapped to the trolley, therefore, it is impossible to avoid the loss incident to transmission.

In the applications where the load density is high and feeder circuits are short it is of course, desirable to reduce the value of cushioning resistance to a minimum. To enable the use of lower values of cushioning resistance, generators with wider commutating limits than ordinarily found in standard commutating-pole generators must be employed. To increase the commutating limits of a direct-current generator it is necessary to reduce the leakage flux of the commutating-pole circuit in order to increase the value of load current at which saturation of the commutating pole occurs. This reduction of leakage is most effectively obtained by distributing the commutating-pole field winding so that the length of the path of the leakage flux is increased.

This increase in the leakage path is most effectively obtained by distributing the commutating-pole field winding over the main field poles as shown in Fig. 3. This part of the commutating-pole field winding which is not on the commutating pole itself is called the compensating winding. Armature current flows through the compensating winding in such a direction as to neutralize the flux set up by the current in the armature conductors at the points where they originate.

*A Compensated Commutating-Pole Generator* has a greater commutating capacity, because the lower leakage flux around the commutating-pole permits higher values of commutating-pole exciting current, and consequently armature current, to flow before saturation of the commutating-pole circuit begins to affect commutation. In a compensated generator the commutating-pole leakage flux may be decreased as much as 50 percent of that in a non-compensated generator, so that the total flux, (useful plus leakage) at the base of the pole is reduced, with a corresponding increase of the maximum load at which saturation of the commutating pole magnetic circuit begins to affect the useful flux that links the coils undergoing commutation. Thus the maximum value of armature current that can be commutated without undue sparking or flashing at the commutator is higher. The compensating winding prevents armature cross magnetization and consequently reduces the maximum voltage between any two commutator bars, thereby, reducing the possibility of arcing or sparking between commutator bars.

The compensating winding reacts to neutralize the armature magnetizing forces that ordinarily cause shifting of the main field flux under load to produce a flux distribution under the field poles, as shown in Figs. 1 and 2, curves *A*. The distribution of the flux under the pole is also a measure of the voltage gen-

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erated in the coils cutting this flux, and a peaked flux wave, as shown in curves *A*, indicates that the voltage between adjacent commutator bars is a maximum between the bars connected to the coils cutting the maximum field, which is located at the trailing pole tip in a non-compensated generator. Current flowing in the compensating winding, Fig. 3, in a direction opposite to that in the armature conductors, prevents armature cross magnetization and the resultant flux distribution

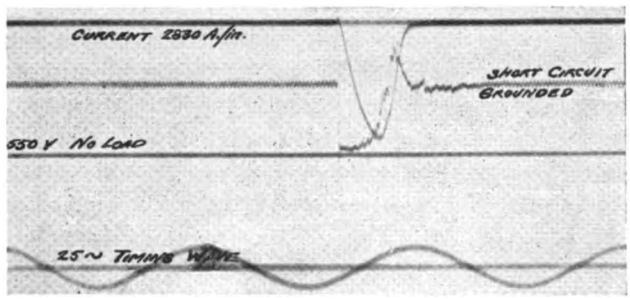


FIG. 5—OSCILLOGRAM OF A SHORT-CIRCUIT ON A COMPENSATED GENERATOR OPENED BY A HIGH-SPEED CIRCUIT BREAKER

under the pole faces is approximately the same under load as at no load. With uniform distribution of flux, the voltage between adjacent commutator bars is uniform, and consequently the maximum voltage between any two bars is reduced.

The inherent design of the compensated commutating-pole generator is such that the effects of armature reaction are neutralized under the pole face as well as in the commutating zone, and the maximum value of current at which saturation of the commutating-pole magnetic circuit occurs is considerably higher than in any other type of direct-current generator. The increased commutating limits of this type of generator make it particularly suitable to a type of service where the unit is required to commutate heavy overloads at frequent intervals. Hence this type of generator is best suited for systems such as shown in Fig.

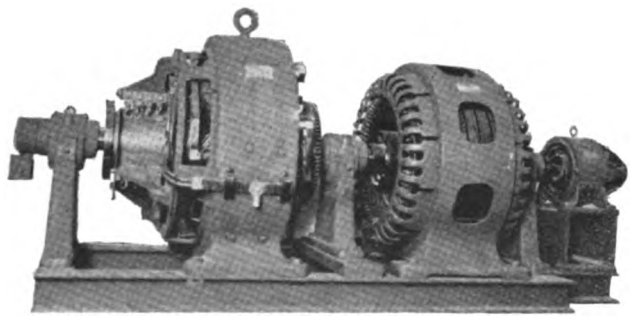

FIG. 6—A SYNCHRONOUS MOTOR-GENERATOR SET
The generator is of the compensated type and is rated at 300 kw, 600 volts. The bedplate is made from electrically welded structural steel. The central bearing pedestal may be removed without disturbing either motor or generator.

4, where the resistance between the generator and the first point tapped to the trolley is relatively low.

## HIGH-SPEED CIRCUIT BREAKER

There are certain applications where it is impossible to secure sufficient cushioning resistance in the feeder circuits to afford protection to the generators when they are protected by standard breakers. For such applications, the high-speed direct-current circuit breaker has proved very effective. As its name implies, this is a high-speed breaker of the contactor type, designed to open under short-circuit conditions with such rapidity that the maximum value of current is limited in from 0.007 to 0.012 second and complete rupture of the arc is accomplished in 0.015 to 0.020 second. The period that the short-circuit remains on the generator is so short that excessive heating of the brushes and commutator does not occur and, consequently, the film of conducting vapors necessary to spread the arc between brush arms is not developed, and flashing is prevented. An oscillograph record is shown in Fig. 5 of a dead short-circuit on a 300 kw, 600 volt, compensated, commutating-pole generator protected by a 1200 ampere high-speed, direct-current breaker. The fault current was limited to 3400 amperes in 0.0068 second with complete opening in 0.0135 second. The only resistance external to the generator was that necessary to connect the quick-acting short-circuiting switch into the circuit, with one million circ. mil cables.

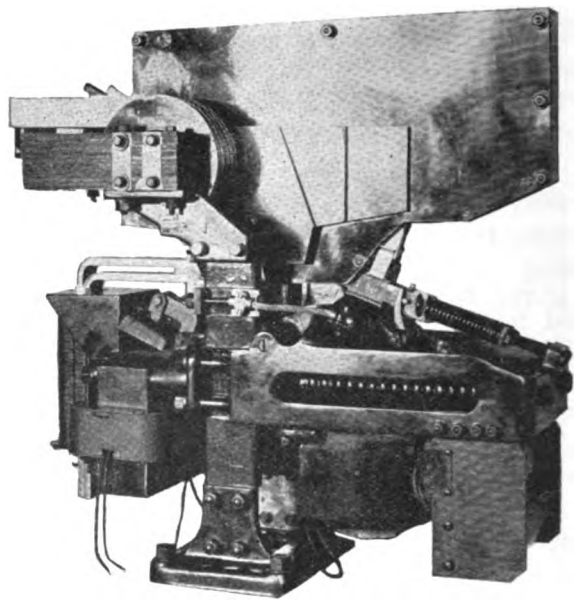

FIG. 7—A 1200 AMPERE, 1500 VOLT HIGH-SPEED CIRCUIT-BREAKER

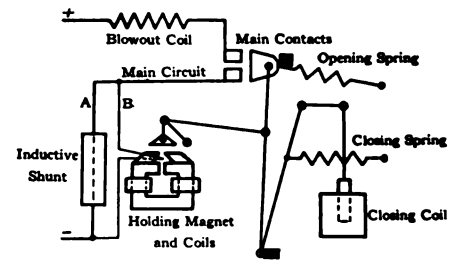


FIG. 8—SCHEMATIC ARRANGEMENT OF A HIGH-SPEED CIRCUIT-BREAKER

The high-speed circuit breaker is essentially a protective device and should be applied as such, and not as a combination feeder breaker, fault detector and machine protective device. To secure the high rate

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of contact opening required to protect a generator adequately during fault conditions, the high-speed breaker is of the contactor type, supplied with powerful magnetic blow out coils, but without auxiliary arcing tips. It secures its quick acting features by its method of tripping and its arrangement of springs and levers.

To secure the most satisfactory operation of a high-speed breaker as a protective device it should be located in the leads of the generator which it is to protect, and not in the feeder circuit. Its tripping circuit should be calibrated so that opening will occur only at values of current which would cause flashing at the commutator. Normal overloads and fault currents below the flashing point on the generator should be opened by the ordinary carbon circuit breakers or contactors located in the feeder circuits.

When high-speed breakers are used in feeder service they must combine the features of a standard piece of switching apparatus with that of a quick-acting breaker, in order to secure a short-circuit detector, overload trip breaker sufficiently rugged to handle normal switching operations, and yet be highly sensitive to afford protection to the generator due to faults on the trolley system. The problem of isolating faults on long, high-resistance feeder circuits where the fault current is less than the normal overload setting of the feeder breaker greatly complicates the problem, as a circuit breaker calibrated to open on the minimum fault current will, in practically all cases, open up when a heavy legitimate load is thrown on the trolley system. Operation under such conditions results in an undue number of breaker operations with resultant high maintenance and upkeep on the high-speed breakers.

SUMMARY

Simplicity in substation apparatus has been the criterion by which many operating companies have been guided; and they have been skeptical about applying any type of apparatus for protective purposes that will require periodic inspection and maintenance, when the same degree of protection can be secured easily by the selection of suitable generating equipment, and its proper application to the system it supplies.

With a better understanding of the factors causing flashing at the commutator on direct-current generators, and knowledge of ways and means of securing protection to the equipment from faults within the mine, most installations can be arranged so as to render the substation equipment inherently self-protecting by means of ordinary slow-speed interrupting devices.

# Recent Developments in Permissible-Type Equipment

W. D. TURNBULL
General Engineer,
Westinghouse Electric & Mfg. Co.

THE motor shown in Fig. 1 has been literally explosion tested in the laboratories of the Bureau of Mines. Their method is to insert into the motor case a spark plug, fill the motor with an explosive mixture of natural gas, seal it in the manner provided, place it in a steel chamber containing a similar gaseous mixture and apply a spark inside the motor. The object is to determine the suitability of the motor to withstand an internal explosion without injury to itself or without propagating the explosion to the surrounding gases. This is one of the tests the apparatus must pass to meet the approval of the Bureau of Mines as permissible.

The term permissible, as applied to electrical apparatus, is one that has been adopted by the United States Bureau of Mines for equipment it has approved for use in gaseous mines. All such equipment is tested and inspected by the Bureau, and must meet certain requirements before it is considered suitable for being rated as permissible. This approval is identified by a plate, such as shown in Fig. 2, which is issued to the manufacturer for mounting in some conspicuous place on the machine. In addition to identifying the approval, this plate specifies certain precautionary measures that must be followed to maintain the permissibility of the apparatus. These cautions are for the use and guidance of the operator as he, in accepting

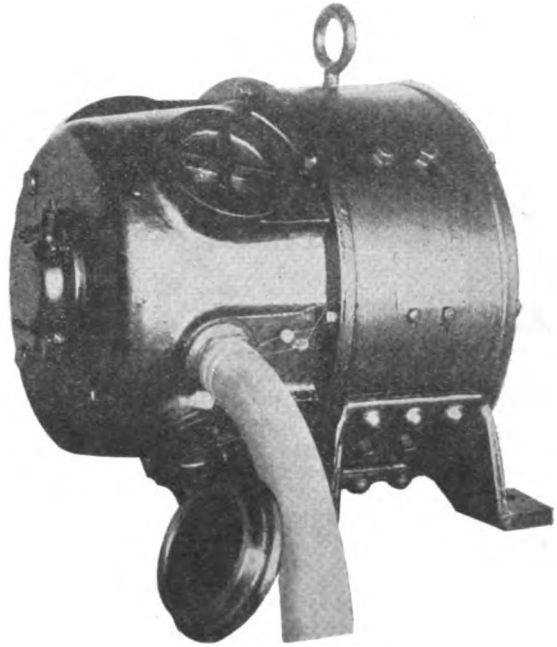

FIG. 1—A PERMISSIBLE DIRECT-CURRENT MINE MOTOR
All joining surfaces are made wide and are machined to give a high resistance creepage path to gases. All removable parts may be sealed when in place to prevent the opening of the motor by unauthorized persons.

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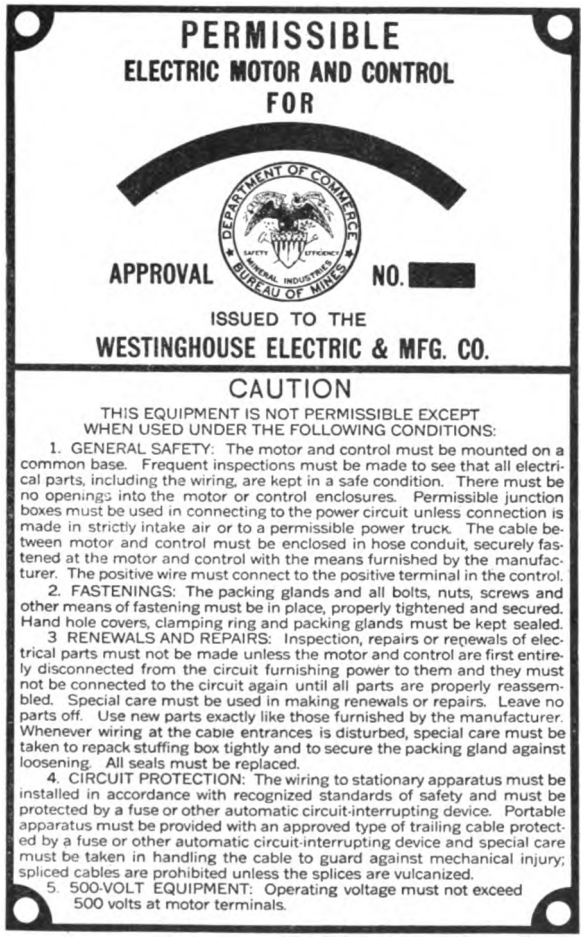
the machine approved by the Bureau, must assume the responsibility of maintaining the apparatus in the same safe condition as when it left the manufacturer's plant; and in making adjustments or repairs must use parts identical with those furnished by the manufacturer on the original machine.

In the early designs of permissible type equipment the main consideration was to design a piece of apparatus which would successfully withstand the test given it by the Bureau of Mines. Not much consideration was given to accessibility. Often the construction and design were such as to require removing a large number of bolts for inspection or to make repairs. The main consideration in the design of permissible type of equipment still is, of course, safety; but correlated with the idea of safety are the factors of accessibility



PERMISSIBLE
ELECTRIC MOTOR AND CONTROL
FOR

APPROVAL NO. [redacted]

ISSUED TO THE
WESTINGHOUSE ELECTRIC & MFG. CO.

CAUTION

THIS EQUIPMENT IS NOT PERMISSIBLE EXCEPT WHEN USED UNDER THE FOLLOWING CONDITIONS:

1. GENERAL SAFETY: The motor and control must be mounted on a common base. Frequent inspections must be made to see that all electrical parts, including the wiring, are kept in a safe condition. There must be no openings into the motor or control enclosures. Permissible junction boxes must be used in connecting to the power circuit unless connection is made in strictly intake air or to a permissible power truck. The cable between motor and control must be enclosed in hose conduit, securely fastened at the motor and control with the means furnished by the manufacturer. The positive wire must connect to the positive terminal in the control.
2. FASTENINGS: The packing glands and all bolts, nuts, screws and other means of fastening must be in place, properly tightened and secured. Hand hole covers, clamping ring and packing glands must be kept sealed.
3. RENEWALS AND REPAIRS: Inspection, repairs or renewals of electrical parts must not be made unless the motor and control are first entirely disconnected from the circuit furnishing power to them and they must not be connected to the circuit again until all parts are properly reassembled. Special care must be used in making renewals or repairs. Leave no parts off. Use new parts exactly like those furnished by the manufacturer. Whenever wiring at the cable entrances is disturbed, special care must be taken to repack stuffing box tightly and to secure the packing gland against loosening. All seals must be replaced.
4. CIRCUIT PROTECTION: The wiring to stationary apparatus must be installed in accordance with recognized standards of safety and must be protected by a fuse or other automatic circuit-interrupting device. Portable apparatus must be provided with an approved type of trailing cable protected by a fuse or other automatic circuit-interrupting device and special care must be taken in handling the cable to guard against mechanical injury; spliced cables are prohibited unless the splices are vulcanized.
5. 500-VOLT EQUIPMENT: Operating voltage must not exceed 500 volts at motor terminals.

FIG. 2—A TYPICAL APPROVAL PLATE ISSUED BY THE U. S. BUREAU OF MINES

This particular approval was issued to cover a gathering pump equipped with a 5 hp motor and full magnetic pushbutton-operated control. The name of the pump and the approval number go in the blank spaces at the top of the approval plate. The bottom part of the plate contains the caution notes which are to be followed by the operator in maintaining the permissibility of the equipment.

and reliability. Several of the manufacturers are following the practice of supplying liberally rated apparatus so as to decrease the necessity for inspection or repairs. The cases or covers, wherever possible, are made so that they can be removed for inspection or repair with minimum labor and time, and by loosening or taking off as few parts as possible. Thus the chance of their being assembled improperly by the omission of bolts, nuts, or clamping devices that are essential to their safety and permissibility is decreased.

An example of this design is the controller shown in Fig. 3. This controller is of the full magnetic, push-button operated type in which a double-pole contactor,

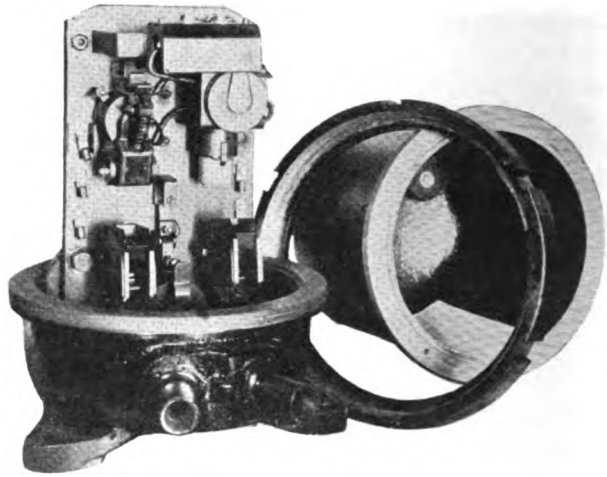


FIG. 3—A SCREW-TYPE ENCLOSURE FOR A CONTROLLER

equipped with blowout coils and arc shields, is used to open both sides of the direct-current circuit. An accelerating contactor operated on the counter e.m.f. principle is mounted above the line contactor, and automatically cuts out the resistor when the motor comes up to a predetermined speed. The resistor for starting is mounted on the back of the panel. The overload relay and pushbutton are mounted on the front of the panel at the top, as shown in the picture. The lead entrances are of the latest, approved type, generally referred to as the packing gland type.

With this control multi-conductor cable is used, a two-conductor cable being used for the power leads and a three-conductor cable from the controller to the motor. This permits an assembly of the apparatus in which all of the connections are made inside of the permissible cases, thus eliminating the possible

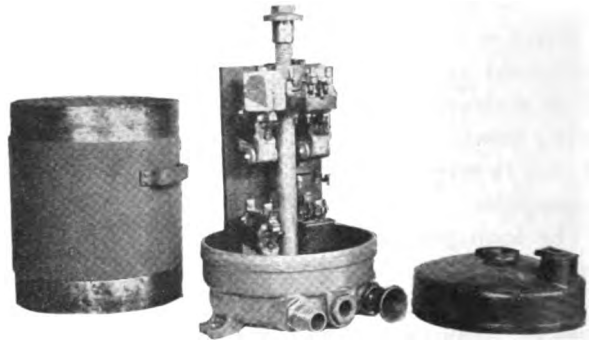


FIG. 4—A SINGLE BOLT-AND-NUT-TYPE OF CONTROLLER ENCLOSURE

hazard of sparking or flashing at loose terminals or connections. The case consists of three main parts, the bottom casting, the cover or top casting, and the screw type clamping ring. The bottom casting is provided with a flanged step joint. The top casting or cover which sets down over the whole panel is machined to fit the lower casting. The clamping ring fits

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down over the top cover and screws onto the bottom casting, holding the two essential parts, the bottom casting and cover together. To inspect the controller or to make repairs it is necessary merely to unscrew the clamping ring and lift off the top cover.

A different design that achieves the same purpose is shown in Fig. 4. In this design the screw clamping ring is omitted, and the assembly is held together by means of a single nut on top of the controller. This nut, when tightened down, holds the assembly of the bottom, side, and top castings together; when taken off, it permits the same accessibility as just described.

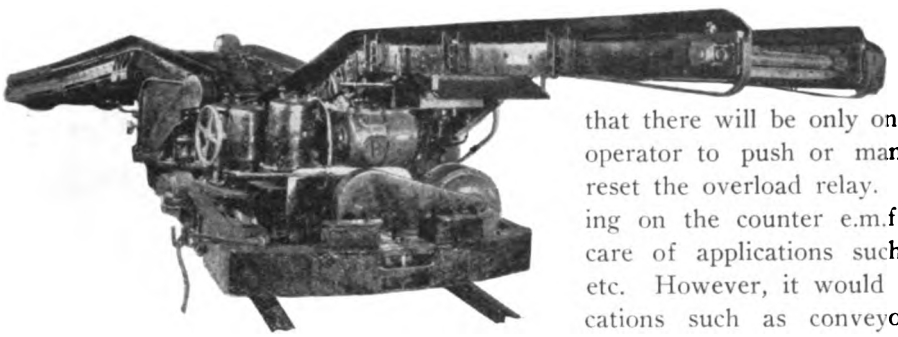

FIG. 5—A RECENTLY DEVELOPED LOADING MACHINE

Designed for use in narrow rooms or entry driving, and equipped with permissible-type electrical apparatus. The three motions of the machine, i.e., the front or gathering conveyor, the rear or loading conveyor, and the propelling motion, are each controlled by a small drum controller as shown in Figs. 4 or 5. These are shown mounted on the side of the machine.

Mechanization has resulted in the use of a considerable amount of electrically-driven apparatus which is used at or near the mining face and for which there is a demand for electrical apparatus of the permissible type. Probably the first among these is the cutting machine, which has for a number of years been equipped with permissible apparatus. The loading machine is a much more recent development, the use of which has grown rapidly within the last few years. The loading machine, like the cutting machine, being a face-operated piece of apparatus, should have permissible electrical equipment if the machine is to be operated in a gaseous mine. Many of the loading machines have separate motors on the different drives. Some of these drives require speed and reversing control equipment. One of the recent developments of permissible equipment is a drum controller which provides four points of acceleration for both forward and reverse. This controller is designed for either 230 or 550 volts direct current.

Dimensions present one of the first obstacles encountered in the design of electrical apparatus to be used on loading machines. The manufacturer of the loading machine is anxious to make his machine as suitable for as many different fields or systems of mining as possible, and to do this rigid space economy must be practiced. To conform with the general scheme of compactness, considerable ingenuity is required in the design and manufacture of control apparatus, especially of the permissible type, so that it will perform the severe service required on certain motions of loading machines, and be sufficiently small in size to fit into the limited space available.

Some mining apparatus does not require any special skill in its operation except for the electrical apparatus. This has brought about a demand from some of the larger operators for electrical equipment of the permissible type for application on pumps, fans, rock dusting machine and conveyor installations, that will be arranged for pushbutton operation and so designed that there will be only one or two buttons or plungers for the operator to push or manipulate to start or stop the motor or reset the overload relay. The controller shown in Fig. 3, working on the counter e.m.f. principle, is well adapted to take care of applications such as rock-dusting machines, pumps, etc. However, it would not work very successfully on applications such as conveyor drives, where the equipment would be required to start with widely different conditions of loading, and with considerable variation in line voltage, as is generally the case when the conveyors are operated at or near the face. For such applications a controller has recently been developed which is of the full magnetic push button operated type, similar to the one described in connection with Fig. 3, except that it employs time-limit acceleration and in the larger sizes is provided with an additional step of acceleration. Time-limit acceleration gives positive assurance that the motor will accelerate regardless of the load or the voltage provided the operating limitations of load and voltage are not exceeded.

Electrical apparatus is available that will operate on practically any of the applications requiring permissible equipment. Many operators have found that, aside from the safety factor, the special totally enclosing feature and the rugged construction makes permissible type equipment very desirable on certain installations where the apparatus is liable to be injured by moving material, or where there are extreme dust conditions or water drippage.

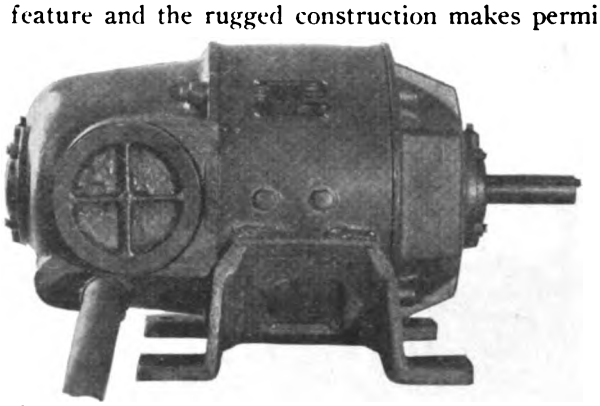

FIG. 6—A SMALL MOTOR OF THE PERMISSIBLE TYPE DESIGNED PRIMARILY FOR ROOM HOISTS AND SMALL CONVEYORS

This motor is arranged for full voltage starting, on either 230 or 550 volts. As the motor is used on equipment frequently moved about by the men themselves the weight and size is kept to an absolute minimum. This motor has a continuous rating of 2 to 3 hp depending on the speed; and an intermittent rating of 5 hp. It is equipped with ball bearings, bronze, screw type inspection covers, and stuffing-box type of lead entrance.

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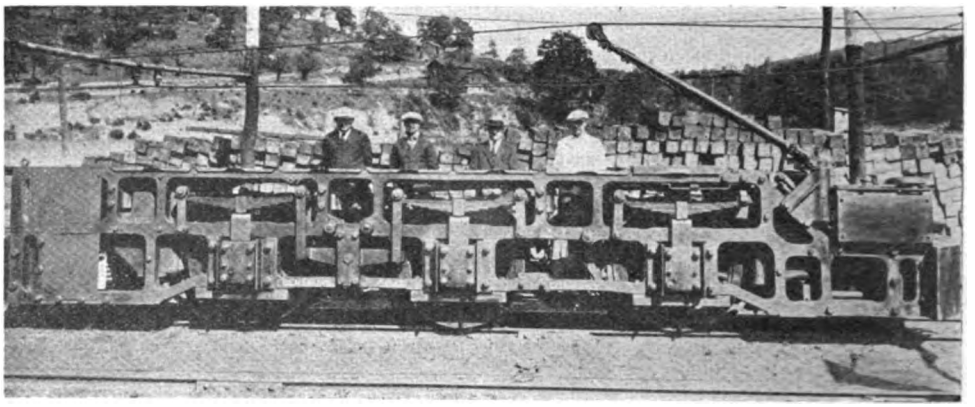

A 22.5 TON THREE-MOTOR LOCOMOTIVE

For 36 in. track guage which can be equipped with a total motor capacity between 270 and 390 hp. Such a locomotive can be equipped with semi-magnetic control or semi-electropneumatic control; and can be provided with air brakes.

# Large Main Haulage Mine Locomotives

G. H. F. HOLY
General Engineer,
Westinghouse Electric & Mfg. Co.

THE main haulage locomotive is an important link in the transportation of coal from the partings or side tracks to the shaft bottom or to the tipples. Recent developments indicate that the tendency in locomotive design is in the direction of the heaviest and most powerful units that operating conditions permit, in order to handle more tons of coal at reduced cost and in less time.

Large units are required when the hauls are long, adverse grade conditions exist, or the output of the mine is large. It is obvious that with larger locomotives fewer will be required, resulting in reduced labor charges and loss of time in dispatching. This is particularly noticeable where the main haul has only a single track, and passing tracks are required.

*Increased Motor Capacity*—Formerly the motor capacity was of the order of 10 to 12 hp per ton. The motor capacity that can now be applied on locomotives is 12 to 20 hp per ton. Formerly two 90 to 95 hp motors were considered desirable for 13 and 15 ton locomotives, while in recent years motors have been designed of 115 to 150 hp capacity each for 13 and 15 ton locomotives. Even where the motor design has been confined to a 36 in. gauge track, 130 hp motors are available for application on 13 and 15 ton locomotives having two-motor equipment.

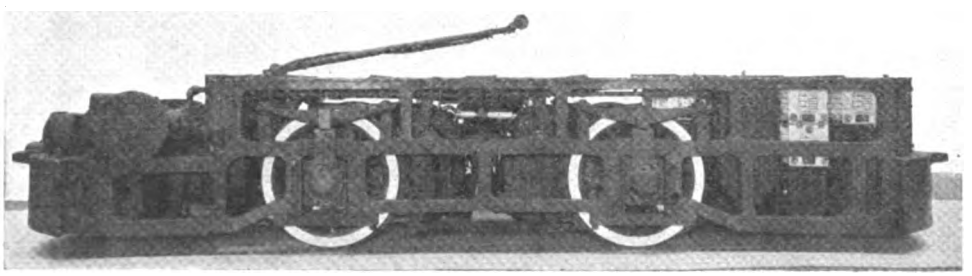

FIG. 1—A 20 TON TWO-MOTOR LOCOMOTIVE, WITH A CAPACITY OF 300 HP
Equipped with air brake, air sanders, semi-electro-pneumatic single-end control.

*Larger Rails and Trolleys*—Mines equipped with these large locomotives necessarily require heavy rails, good bonding, and good trolley wire construction. In Table I is given a recommended rail weight for locomotives from 13 to 37.5 tons. Quite a number of coal companies operating 15-ton locomotives in tandem or separately have their mine equipped with 85 lb. rails and some mining companies are now installing 6/0 trolley wire.

*Heavy Grades and Long Hauls*—Severe adverse grade conditions in a great many cases are the ruling factor in the selection of large locomotives with large capacity motors. Such a condition can be illustrated by a 12 000 foot haul one way, of which the average grade against the load is approximately four percent for 8000 ft., and the maximum grade six percent for 600 feet, with the remainder of the haul varying from 0.1 to 0.5 percent in favor of the load. Over a period of 20 days, two 22.5-ton locomotives averaged 13 trips per day, producing at the surface 682 loaded cars.

In order to produce the above output it was necessary for each locomotive to average approximately 41 miles a day in an eight-hour shift. It is obvious that, under the severe operating conditions, three and possibly four 15-ton locomotives would have been required which, in turn, would have increased the labor charge and no doubt cause confusion, particularly from a dispatching standpoint, as this was a single-track mine with only one passing track at the top of the 8000-foot grade.

*The Haulage Capacity* of locomotives on grades up to and including five percent are given in Table II, on the basis of mine cars equipped with anti-friction bearings.

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*The Control* for these locomotives is of the series-parallel type, the transition from series to parallel being made by progressive steps on the accelerating drum of the controller, from the full-running position of the motors in series to the accelerating position with the motors in parallel. Fig. 6 illustrates semi-magnetic control for a three-motor outfit and Fig. 7 the wiring diagram for a two-motor control using electro-pneumatic switches. Overload protection is provided by overload relays.

TABLE I—RECOMMENDED RAIL WEIGHT

| Weight of Locomotives in Tons | 2-Axle Locomotive | 3-Axle Locomotive |
|---|---|---|
| 13 | 40 to 50 lbs. per yd. | — |
| 15 | 50 lbs. per yard | 40 lbs. per yard |
| 20 | 60 lbs. per yard | 50 lbs. per yard |
| 22.5 | 60 lbs. per yard | 50 lbs. per yard |
| 25 | 70 lbs. per yard | 60 lbs. per yard |
| 30 | — | 70 lbs. per yard |
| 35 and 37 5 | — | 80 lbs. per yard |

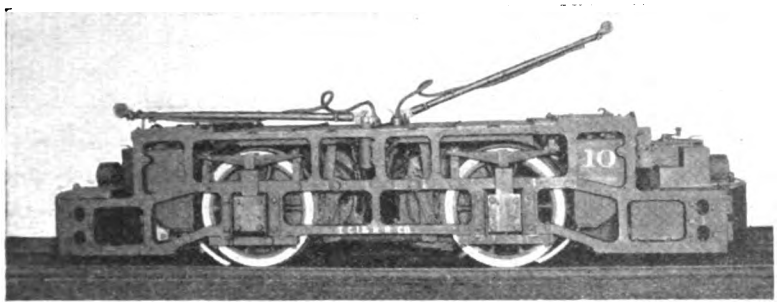

FIG. 2—A 15 TON TWO-MOTOR LOCOMOTIVE
Arranged for double-end operation with semi-magnetic control. This locomotive has a total motor capacity of 260 hp on 36 in. gauge track or 300 hp when arranged for 42 in. gauge track.

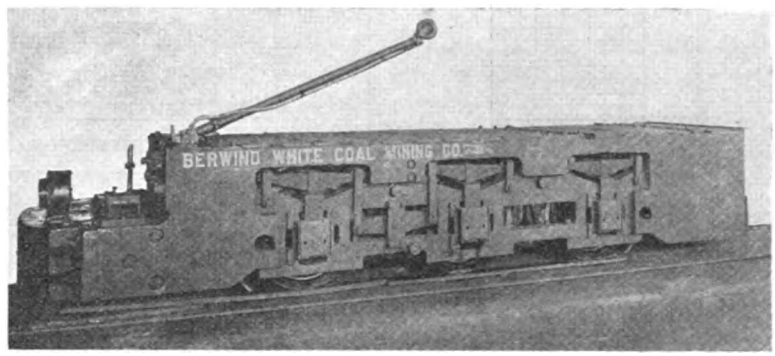


FIG. 3—A 35 TON LOCOMOTIVE SUITABLE FOR 36 IN. GAUGE TRACK
Can be equipped with three motors having a total of about 400 horse-power capacity, forced ventilation, and semi-magnetic control.

*The Speeds* of two and three-motor locomotives are shown in Fig. 8. Curve *A* illustrates the locomotive speed at the rated tractive effort for the corresponding rated drawbar pull when the locomotive is equipped with 150 hp motors and curve *B* when it is equipped with 125 hp motors. It will be seen from either one of these curves that the speed change is gradual and apparently not excessive when going from the rated tractive effort of the two-motor 25-ton locomotive to the two-motor 15-ton locomotive or from the three-motor 37.5-ton locomotive to the three-motor 20-ton locomotive. The speed of the two-motor 15-ton locomotive, when equipped with 150 hp motors at a rated tractive effort of 7800 lbs. is approximately 10.25 miles an hour, and at half load or 3900 lbs. tractive effort the speed is approximately 12.5 miles per hour. The drawbar pull and speeds for two-motor and three-motor locomotives equipped with motors of the characteristics shown by Curves *A* and *B*, are given in Table III.

*Maintenance*—With the larger motor capacity, in addition to increasing the tonnage and reducing the number of locomotives, motor maintenance is reduced, as the slipping point of the wheels on locomotives equipped with 15 to 20 hp per ton is quite close to the normal rating of the motor, while with locomotives having 12 to 15 hp per ton the slipping point of the wheels may be as high as 20 to 25 percent above the normal rating of the motor. To insure ample bearing capacity the motors are equipped with tapered roller bearings.

*Curves*—The two-motor locomotives are suitable for hauling trips around curves as low as 50-foot radius and the three-motor locomotive for curves of 90-foot radius. As a protection for three-motor locomotives against derailment on sharp curves, it is generally desirable to provide a guard rail on the inside of both the inner and outer rails on curves.

*Long Hauls* — Hauls of two to three miles are not uncommon at present, and as the development of mines is progressing at a rapid rate due to increase in the use of loaders and cutters, the average haul will in some mines approximate five miles one way from the surface or shaft bottom. Irrespective of grade conditions, such a haul requires locomotives of increased speeds as well as increased capacity.

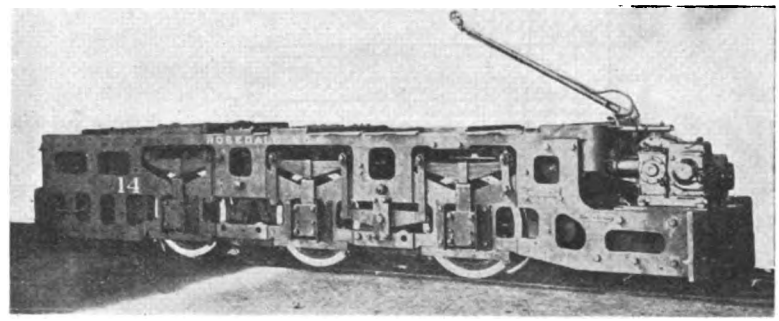

FIG. 4—A 35 TON LOCOMOTIVE FOR 42 IN. GAUGE TRACK
Equipped with electro-pneumatic control, air brakes, forced ventilation, and which can be provided with a total of 450 hp for three motors.

There is now under construction a 38-ton locomotive equipped with three motors and semi-magnetic

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control for service where the grade conditions are severe and average 2.4 percent for a haul of four miles. The maximum grade in this haul is 5.6 percent for 1000 feet. In order to get out the required tonnage, the locomotive with the loaded and empty trip must make a round trip every hour, and 15 to 20 percent of this time must be allocated to make up the empty and loaded trip at the tipple and at the parting. Such a production schedule requires not only a heavy locomotive, but also a locomotive of ample motor capacity and high speed. High-speed equipment will be required, as the round-trip haul is approximately eight miles. The rated drawbar pull of the 38-ton locomotive will be 19 000 lbs. at eight miles per hour. The speed will be approximately nine miles per hour when hauling 60 cars up the average grade.

TABLE II—HAULING CAPACITY OF MINE LOCOMOTIVE

| Weight of Locomotive in Tons | Tons Trailing Load | | | | | |
|---|---|---|---|---|---|---|
| | Level Track | Percent Grade | | | | |
| | | 1 | 2 | 3 | 4 | 5 |
| 13 | 650 | 210 | 120 | 85 | 60 | 50 |
| 15 | 750 | 240 | 140 | 95 | 70 | 55 |
| 20 | 1000 | 320 | 185 | 125 | 95 | 75 |
| 22.5 | 1125 | 360 | 210 | 145 | 105 | 80 |
| 25 | 1250 | 400 | 230 | 160 | 120 | 90 |
| 30 | 1500 | 480 | 280 | 190 | 140 | 110 |
| 35 | 1750 | 560 | 325 | 220 | 165 | 125 |
| 37.5 | 1875 | 600 | 345 | 235 | 175 | 135 |

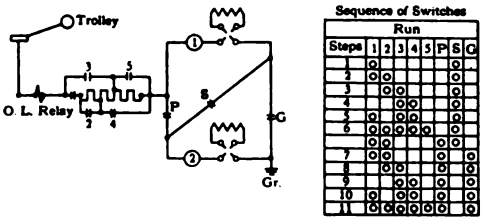


FIG. 5—DIAGRAM OF MAIN TWO-MOTOR CONTROL CIRCUITS

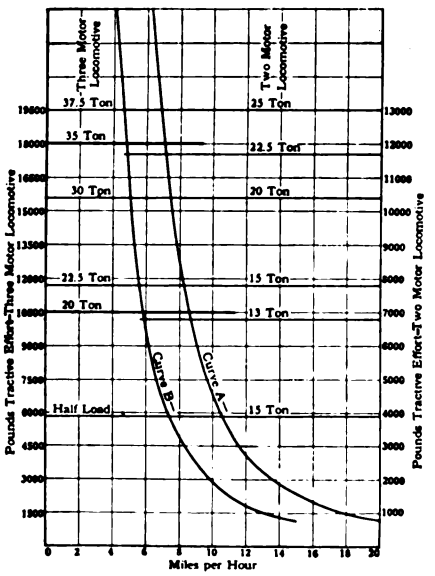


FIG. 7—TRACTIVE EFFORT CURVES OF TWO AND THREE-MOTOR LOCOMOTIVES

A—for 150 hp motors; B—for 125 hp motors

*Equalization*—The track conditions on the main haulage are generally such that good alignment and fair surfacing can be depended upon. The track conditions adjacent to the face, however, are more severe, as this remains more or less temporary until final grading for permanent track is made. To meet the track irregularities that can and do exist on the main haulage, these large two-motor locomotives are arranged with a cross equalizer between the weight-carrying springs on one pair of journals. On the three-motor locomotives, side equalizing bars are connected on each side of the locomotive between the weight-carrying springs of two pairs of driving-axle journal boxes, and a cross equalizing bar for the weight carrying springs on one axle. This construction provides a three-point support for the spring carried parts of the locomotive, and permits the wheels to adjust for track irregularities that might exist between rails or on the rail themselves, and insures a more even weight distribution at the wheel treads, which reduces the tendency to derail.

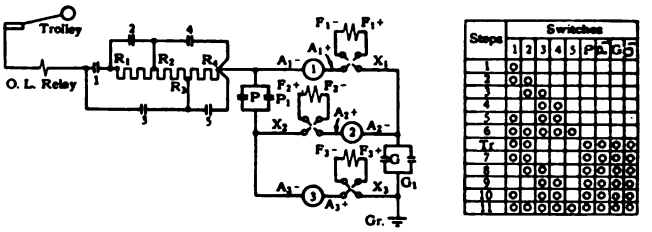


FIG. 6—DIAGRAM OF MAIN THREE-MOTOR CONTROL CIRCUITS

TABLE III—RATED DRAWBAR AND SPEEDS OF MINE LOCOMOTIVES

| Locomotive Weight in Tons | Drawbar Pull in Lbs. | Miles Per Hour | |
|---|---|---|---|
| | | Two-Motor | Three-Motor |
| **BASED ON CURVE A** | | | |
| 15 | 7500 | 10.25 | — |
| 20 | 10 000 | 9.5 | — |
| 22.5 | 11 250 | 9.1 | 10.25 |
| 25 | 12 500 | 8.9 | 9.9 |
| 30 | 15 000 | — | 9.5 |
| 35 | 17 500 | — | 9.1 |
| 37.5 | 18 750 | — | 8.9 |
| **BASED ON CURVE B** | | | |
| 13 | 6500 | 7.9 | — |
| 15 | 7500 | 7.6 | — |
| 20 | 10 000 | 7.1 | 7.9 |
| 22.5 | 11 250 | 6.8 | 7.6 |
| 25 | 12 500 | 6.6 | 7.4 |
| 30 | 15 000 | — | 7.1 |
| 35 | 17 500 | — | 6.8 |
| 37.5 | 18 750 | — | 6.6 |

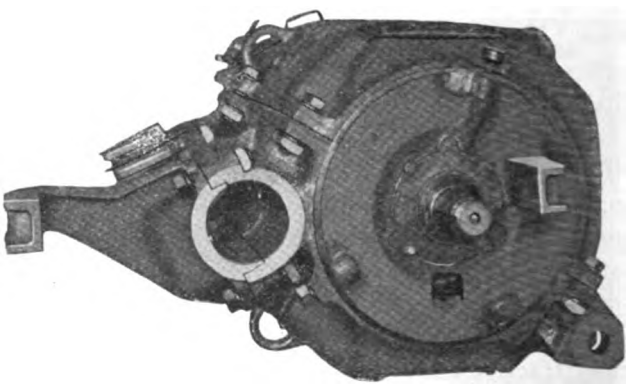

FIG. 8—A 150 HP MINE LOCOMOTIVE MOTOR

The electrical manufacturers are co-operating with the coal operators to carry out their program of mechanization of mines, and are helping to solve one troublesome phase by building dependable mine transportation units of ample capacity and speed to deliver the increased output.

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# Trolley Wire for Mine Service

H. N. RICHARDS
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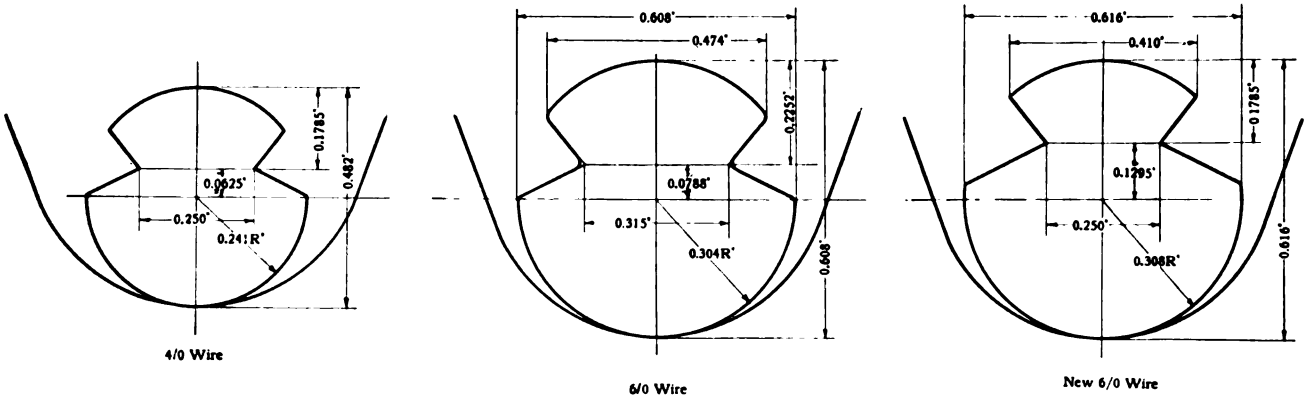
IN the larger coal mines both the production and the length of main mine haulage ways have been materially increased. The number of cars in the trips and the size of the locomotive to pull these trips have both increased. Twenty-ton locomotives are in use and in one case thirty-eight ton locomotives are being installed. Thirteen-ton units are being hooked in tandem in many mines. As the haulage lengths are further increased and efforts are made for greater production, still more powerful locomotives will undoubtedly be used.

The increased current to be collected by these locomotives must be considered. This is particularly important where 250 volt systems are used. While it is true that the trolley line may be paralleled with feeder cables of sufficient size, the area of the surface of the contact wire on which the collector bears must be taken into consideration.

Considerable trouble has been experienced with pitted that the effective area is reduced in places to 2/0 size. As the trolley wire is not paralleled with feeder cable in many entries, it carries all of the current. This reduced section is not sufficient to maintain proper voltage at the mining face.

Considerable trouble also results from trolley wire breakage caused by slate falls. The mechanical strength of the wire is lowered both by the reduced section, and by the wire being annealed by the heavy current collected from it and the burning caused by the arcing of the trolley wheel. If the 6/0 wire is used until it is worn down to a 4/0 section and then moved forward, these troubles will be reduced. Better operation for the gathering locomotives will thereby result.

Cross-sections of a 4/0 grooved wire and the present 6/0 wire in contact with trolley wheels are shown in Figs. 1 and 2. The area of the 4/0 section is 211 600 circ. mils, while that of the 6/0 section is 336 400 circ. mils, or 59.4 percent more. The radius of the lower




FIGS. 1, 2, 3—TROLLEY WIRE DIMENSIONS

4/0 wire on this heavy service. The comparatively small area of contact surface between the trolley wheel and the wire causes both the trolley wire and wheel to heat. The tendency of the wheel to strike the jaws of the clamps supporting the 4/0 wire, particularly if the wheel is worn, causes it to jump. This burns both the trolley wheel and wire. Soon the wire becomes badly pitted, and presents a rough, uneven surface. The life of the wire is thus considerably decreased.

Several mining companies, particularly in western Pennsylvania, have replaced the 4/0 wire on their main haulage ways with 6/0 grooved wire. They all have found that better operation, less arcing, and increased life of the trolley wire has resulted from this change. The 6/0 wire has another decided advantage. It is customary to move the trolley wire on main haulage ways forward into the entries when it becomes worn. Frequently the 4/0 size becomes so badly worn and lobe, which is in contact with the collector, of the 4/0 grooved wire is 0.241 in. while the radius of the 6/0 section is 0.304 in. Figs. 1 and 2 show that the surface of the wire in contact with the wheel on the 6/0 size is about 50 percent greater than on the 4/0 size.

There is an increase of 0.079 in. with the 6/0 wire over the 4/0 in the distance from the contact surface of the wire to the groove in which the mine clamp jaws grip the wire. There is only 1/16 in. greater width of the 6/0 wire over the 4/0 in the groove. Taking this into consideration it is apparent that when the 0.608 in. diameter of the lower lobe of the 6/0 wire is compared with the 0.482 in. diameter of the lower lobe of the 4/0 wire, much better wheel clearance will result. In fact, arcing caused by the trolley wheel striking the jaws of the clamp is practically eliminated.

It is less difficult to install 6/0 wire than 4/0. The roll which causes trouble with 4/0 wire, particularly when it is being carried around curves is eliminated

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due to the increased stiffness of the wire. Thus considerable time and trouble is saved when the wire is placed in the clamp. The additional mechanical strength reduces the number of trolley wire breaks. This advantage is very noticeable in mines having poor roof.

A proposed change in the 6/0 grooved section is shown in Fig. 3. The distance across the grooves is the same as with the 4/0 grooved wire. The cross-sectional area is the same as the present 6/0 wire. This change throws the center of the wire 0.1295 in. below the groove in place of 0.0788 in. as on the present design. The distance from the surface of the bottom lobe to the groove is 0.3828 in. on the present design and 0.4375 in. on the proposed section. Thus a greater amount of copper is available in the bottom lobe of the wire which is subject to wear. This will result in increased life of the wire.

On the present design the maximum distance across the upper lobe against which the jaws of the clamp bear is 0.474 in., and the maximum distance across the bottom lobe is 0.608 in. On the proposed design the distance across the upper lobe is 0.410 in., and the distance across the lower lobe is 0.616 in. When this wire is installed in the clamp, the distance across the jaws of the clamp will be 0.072 in. less than with the present design. When this is taken into consideration, together with the difference in height mentioned in the preceding paragraph, it is apparent that arcing caused by the trolley wheel striking the jaws of the clamps will be considerably reduced.

# Fluid Governors for Prime Movers

## II--Type Characteristics

HENRY F. SCHMIDT

THE pressure-volume characteristics of the three well-known types of centrifugal pump runners are shown in Fig. 10. With the vanes curved backwards, the pressure diminishes with increased quantity of flow shown at (a). With radial vanes, the pressure decreases very slightly with increase of flow, though it should, theoretically, remain constant, neglecting the velocity head of the fluid passing through it. With vanes tipped forward, as at (c), the pressure at first tends to increase slightly as the flow increases, up to a point where the increased friction causes the head to decrease. This is due to the fact that the fluid is discharged with a tangential velocity exceeding the tip velocity of the runner.

Broadly speaking, a centrifugal pump runner for governing purposes should have as nearly as possible a straight line characteristic independent of flow over the range through which it must operate. Experience has shown that the straight radial vanes meet this condition best, the pump being designed for a sufficiently large capacity so that even with the maximum instantaneous demand occasioned by a sudden motion of the operating mechanism, the pressure will not decrease sufficiently to interfere with the governing action. This result is obviously accomplished by making the pump runner wider than would be necessary were it designed simply as a pump. The use of guide vanes or of a vortex chamber around the pump runner is undesirable. In the case of guide vanes, the pressure-volume characteristic tends to be more nearly that of a runner with the vanes tipped forward as at (c), giving an increase of pressure with increase of flow. In the case of the vortex chamber, the mass of fluid which is rotating outside of the pump runner tends to make the governing lag, since this mass of fluid is not readily accelerated or retarded with changes of speed of the unit.

In a measure, the use of guide vanes, or rotor blades tipped forward, is desirable in compensating for the drop of pressure caused by the large delivery required with sudden movements of the governing mechanism. However, the governing action of the fluid governors is so rapid that any greater rapidity would probably tend to make the governor over sensitive, and cause hunting.

In centrifugal pumps designed for governing, the pressure is nearly proportional to the square of the speed.

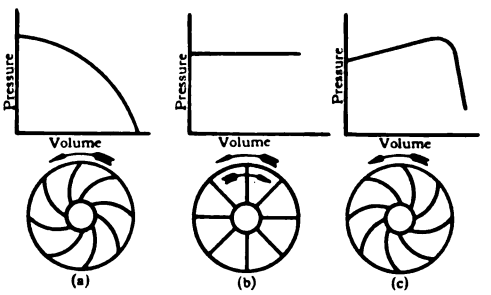


FIG. 10—CENTRIFUGAL-PUMP IMPELLER CHARACTERISTICS

Gear pumps have theoretically the same governing characteristics as centrifugal pumps, provided a constant orifice is provided through which the pump can discharge. However, gear pumps are not suitable as a governing means, except for pump drives or in those applications where no accurate speed regulation is required. The reason is that the ordinarily considerable leakage is seriously influenced by the viscosity of the fluid.

The vane-type pump, in which two or more radially movable vanes act as rotating pistons in an eccentric housing, suffer the same disadvantages from leak-

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age and variations due to slight inaccuracies in machining as do the gear pumps, and consequently are similarily unsuitable for governing.

The characteristics of the scoop-type of governor employing the Pitot tube are similar to those of a centrifugal pump having a very large vortex chamber around the runner. The scoop type of governor is not suitable where large and sudden demands for fluid must be met. Its action depends upon a cup shape rotating receptacle filled with fluid in which the Pitot tube dips. As fluid is drawn away from the cup, fresh fluid must be admitted to the cup to take the place

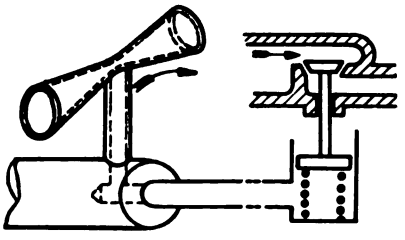

FIG. 11—A VENTURI GOVERNOR FOR GASES

of that withdrawn. Vanes can be provided in a portion of the cup to accelerate the replacement fluid definitely, but there is necessarily a time lag, due to the inertia of the liquid which is not between and definitely driven by the vanes. Furthermore, there is a sudden change of the pressure in the Pitot tube between delivery and no delivery. Theoretically, if the Pitot tube is followed by a frictionless diverging diffusion tube, the velocity of flow through the Pitot tube is converted into static pressures, so that the total static pressure of impact, plus the velocity conversion in the diffusion tube, is a constant. This, however, is not true in practice for the reason that the tube is not frictionless and, also, owing to the nature of the constructions, it is necessary to have an elbow immediately preceding the diffusion tube, making the latter inefficient and thus causing a drop of pressure with increased flow. The Pitot tube type is generally employed with a diaphragm on small turbines where very little flow is required.

A governing arrangement for gases or air is shown on Fig. 11. This employs a Venturi tube, which is rigidly attached to a tubular radial arm fastened to the shaft. A tubular slip joint on the end of the shaft communicates with an operating piston controlling a valve. This arrangement makes use of the property of the Venturi tube that, under certain conditions, the pressure at the throat falls below that of the surrounding medium. Thus, the vacuum created at the center of the shaft is equal to that caused by the centrifugal force of the column of air in the radial arm, plus the reduction of pressure at the throat of the Venturi tube. This arrangement might not be adequate where air is used as the governing means, since, with reasonable peripheral speeds, the vacuum which can be produced is very limited. However, by the use of the Venturi tube, and particularly the Rateau arrangement of a number of Venturi tubes one within the other, the vacuum obtainable for any given peripheral speed can be increased very materially. As will be seen later, there are other applications of the Venturi tube in connection with liquid governors employing either a centrifugal pump impeller or gear or vane pumps.

### EFFECT OF TEMPERATURE AND ATMOSPHERIC PRESSURE

Since the pressure created by a centrifugal pump is directly proportional to the density of the medium acted upon, it is evident that variations in the density of the air or oil used for governing will cause a change of speed. Also, since the pressure created is proportional to the square of the speed, with a fixed setting of the governor spring it is apparent that a change of one percent in the density, causing a change of one percent in the pressure at a fixed speed, will be compensated for by an increase or decrease of one-half of one percent change of speed, using the approximation that for small increments, the square is equal to one plus twice the increment. This approximation will be used throughout this series.

Assuming ordinary room temperature of 70 deg. F., or 531 deg. absolute a change of 531 deg. would make 100 percent change in the density of air or gas, or a change of five degrees, approximately, would make one percent change of density. The speed then of a governor employing gas would change approximately one percent for each 10 degrees F. change.

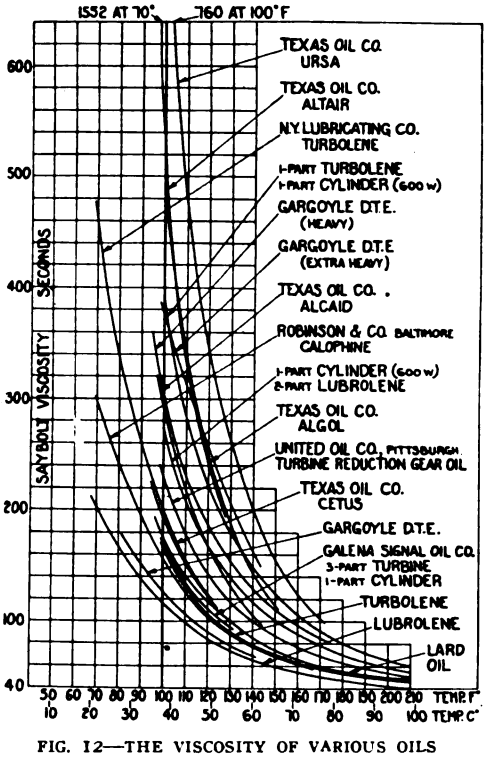


FIG. 12—THE VISCOSITY OF VARIOUS OILS

One inch change of barometer pressure would cause a change of 3.3 percent in the density, or 1.65 percent change of speed. Thus, in the case of gases, the speed change is approximately one percent for 10 degrees F., and one percent for a 0.6 inch change in pressure. As variations of 20 or 30 degrees in the temperature of the engine room and changes of plus

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or minus one inch of barometer are quite normal, it is evident that air and gas are quite unsuited for constant-speed governing. Compensating means of various kinds can be worked out for gases, but these are more or less delicate, complicated and cumbersome, and, therefore, are not considered practicable.

For all ordinary lubricating oils, the density changes approximately one percent for 25 degrees F. change in temperature, or one percent change of speed for approximately 50 degrees change of temperature.

The effect on the viscosity of oil is shown in Fig. 12. The changes in viscosity are very large over the ordinary ranges of temperature which may be encountered in normal operation.

## METHODS OF COMPENSATING FOR PHYSICAL CHARACTERISTICS OF MEDIA

The most obvious means of compensating the centrifugal-type governor, for change of density of the liquid is to make the pump impeller with laminated vanes consisting of alternate strips of copper and steel so arranged that, as the temperature of the liquid increases, the tip diameter increases sufficiently to compensate for the change in density.

Another method of compensating is to immerse the spring in the oil discharged from the impeller. Since the modulus of elasticity of steel decreases with increased temperature, between the ranges of 60 and 250 degrees F., the spring is weakened as the temperature increases. This compensation has been found to amount to approximately three percent change of spring scale for 100 degrees F. increase in temperature, corresponding to 1.5 percent speed compensation for this change of temperature. Thus in the case of oil, simply placing the spring in the oil provides almost complete compensation for temperature changes.

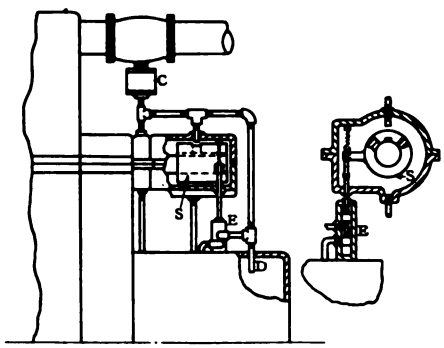


FIG. 13—A SINGLE GEAR PUMP VISCOSITY CORRECTION DEVICE

Another compensation for temperature is obtained by designing the pump impeller with relatively wide blades, so that the radial velocity of the fluid through the impeller is very low, and providing an opening near the center of the shaft for the escape of air. Because of the great difference in density between air and oil, the wide impeller acts as a very effective air separator with the result that the density of the oil increases more rapidly due to the elimination of air than the density decreases due to the increase of temperature. Of course, this compensation of temperature effect has reference only to the starting condition since, normally, the temperature changes very little after the governor has been in operation for half an hour or so, and the air in the oil in the reservoir is eliminated to the amount existing in normal operation.

An arrangement for compensating for the change of viscosity due to temperature in governors employing gear or vane pumps is shown in Fig. 13. The gear pump, not shown, is driven by the shaft and discharges oil through the pipe *D* to the operating cylinder *C* controlling the valve, which is closed as the pressure increases. A branch line from the connecting pipe *D* goes to a compensating valve *E*. Mounted on the shaft, is a sleeve *S* having an arm, connected to the valve *E*. Oil from the gear pump is supplied through a small orifice to lubricate the sleeve and maintain it at the same temperature as the oil discharged from the pump. The sleeve *S* is in effect, therefore, a viscosimeter and the torque developed by the rotation of the shaft will be proportional to the viscosity of the oil. The spring, resists the rotation of the sleeve. Since the pressure built up by the gear pump is higher the greater the viscosity of the oil, it is necessary to bypass part of the oil when the viscosity is high. This is done by the valve *E* since the opening of this valve is proportional to the torque of the sleeve. The valve and spring can be so proportioned that the pressure delivered by the pump will be practically independent of the viscosity.

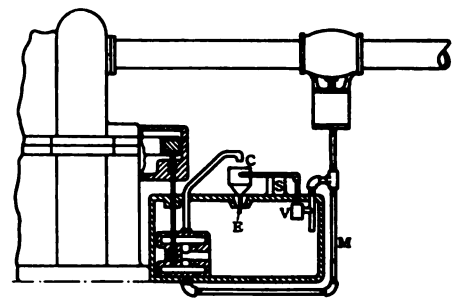


FIG. 14—A TWO-GEAR PUMP VISCOSITY CORRECTION DEVICE

Another method of compensating for viscosity is shown in Fig. 14. Here the compensation for viscosity is obtained by employing two separate gear pumps, one of which supplies the pressure for the governing, and the other which is of relatively large capacity but discharges against practically no back pressure, and is, therefore, independent of viscosity, is employed for obtaining the viscosity correction. This latter pump discharges into a reservoir *C* with an orifice *E* the reservoir *C* being supported by a spring *S*. The reservoir *C* is attached to a lever operating the valve *V*. Since the velocity of flux through an orifice is proportional to the viscosity, if the orifice *E* is fixed, the depth of liquid in the reservoir *C* would depend upon the viscosity, as the quantity of oil discharged by the pump is practically constant. Hence the greater the viscosity, the greater the weight of liquid in the reservoir *C* and the greater the deflection of the spring *S*.

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This in turn, permits the opening of the valve $V$ thus relieving the pressure in the discharge line $M$ as the viscosity increases.

Obviously if the temperature of the oil remained constant, the viscosity would not alter. Consequently any thermostatic control of the temperature would give

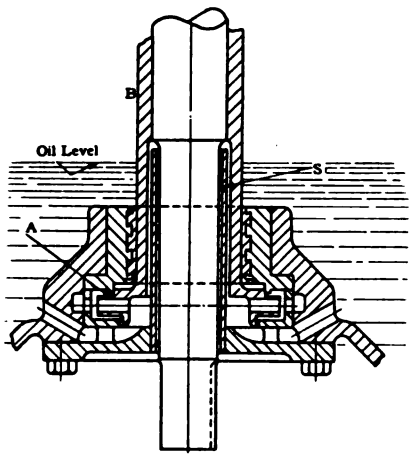


FIG. 15—AN OIL IMPELLER FOR VERTICAL SHAFT TURBINE

the desired result. This could be accomplished by controlling the cooling water or heating the oil to some predetermined temperature. In a governor using air, the supply may be drawn through a coil in the oil reservoir, thus keeping the inlet temperature practically constant, leaving only the effects of pressure change to be corrected.

### METHOD OF SUPPLYING FLUID TO THE PUMP

Except when air is used as the governing means, a most important problem in the designing of fluid governors is to insure a positive supply of liquid to the pump. As the safety of the machine and its satisfactory operation depend entirely upon the governor, it would be out of the question to depend upon the

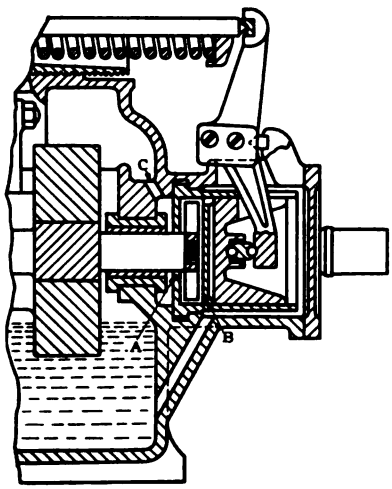


FIG. 16—AN OIL GOVERNOR USING A SPLASH SUPPLY

lifting ability of the pump to draw its supply from a reservoir below it. Some arrangement or device must be employed for supplying the pump under a positive head. The most obvious way in which this can be accomplished is to place the pump in the oil reservoir and drive it through worm or bevel gearing from the main turbine shaft. This method is that first suggested by Ehrhart, and later employed by Sulzer Bros.

Another arrangement is to place the turbine with its axis vertical, with the oil pump on the end of the turbine shaft submerged in the oil reservoir below the turbine, Fig. 15.

The splash system, Fig. 16, may be employed in the case of geared turbines. The gear dips into the oil and throws it into an overhead channel from which it runs by gravity to the impeller on the end of the main turbine shaft. This aerates the oil seriously and requires thorough air elimination.

The oil enters the impeller in Fig. 16 through a narrow annulus $A$ around the shaft and is discharged through radially narrow slots $B$ in the diaphragm between the impeller and the operating piston. As there is only a small amount of leakage past the piston, the impeller is much wider than necessary for the required capacity. The object of this construction is to assure a fixed radial column of rotating oil, so as to avoid fluctuations of pressure due to movements of the operating piston.

The supply port $C$ from the collecting trough, is made large, to permit the air separated in the impeller

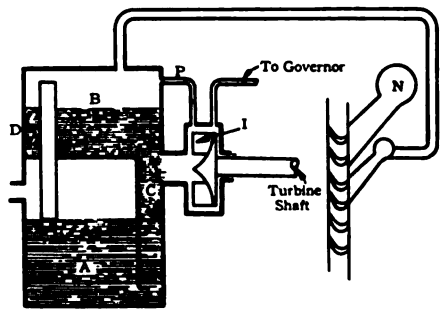


FIG. 17—A VACUUM-TYPE OIL GOVERNOR

to escape. In actual turbines the port $C$ was first made rather small, although it was much larger than would seem necessary, but when the turbine was started, it acted as though the impeller was not getting sufficient oil. The passage $C$ was therefore made larger and the operation much improved.

Still another method of raising the oil into a reservoir is by the use of oil rings. This is not very satisfactory as it is difficult to get a sufficient supply of oil.

The use of auxiliary oil pumps to supply the impeller is obvious. This has the objection that the operation of the main unit is dependent upon auxiliary pumps, which is highly undesirable.

A vacuum system which is applicable to small horizontal units is shown in Fig. 17. The oil reservoir $A$ is connected to a chamber $B$ and a pipe $C$ which extends to the bottom of the oil reservoir $A$. The pipe $C$ also communicates with the inlet to the oil impeller I. A second pipe $D$ furnishes communication between the reservoir $A$, and the chamber $B$. The pipe $D$ is arranged so that when approximately half of the oil originally in the lower reservoir is in the upper reservoir, the lower end of the pipe $D$ will just

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touch the surface of the oil in the reservoir *A*. The chamber *B* has a pipe communicating with an opening near the discharge of the steam nozzle *N*. When steam is turned on the nozzle *N* the ejector action at the discharge of the nozzle creates a slight vacuum in the chamber *B*. Oil from the reservoir, *A* is then drawn into the chamber *B*, through the pipe *C*. The paddle wheel chamber *I* is filled at the same time. This chamber is vented to the reservoir *B* by the pipe *P*, to prevent the paddle wheel chamber from becoming air-bound. The oil will continue to rise in the chamber *B* until the pipe *D* is uncovered at its lower end, permitting air to enter and break the vacuum to such an extent that the level in the chamber *B* is just maintained. Thus, the paddle wheel *I* is positively supplied with oil from the reservoir below the centerline of the shaft. While such an arrangement works, there is always the danger of air leaking into the impeller chamber, causing displacement of the oil and consequent failure of the governing system.

The simplest and what is believed to be the most satisfactory system of supply yet developed is that shown diagrammatically in Fig. 18, employing an ejector. The turbine *A* has mounted directly on the main shaft a centrifugal pump *P* which discharges oil into the pipe *D*. This communicates with the oil operating cylinder *C* through the pipe *B*, and through the

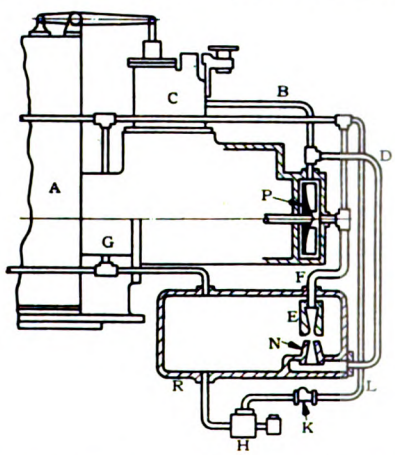


FIG. 18—AN OIL GOVERNOR USING AN EJECTOR SUPPLY SYSTEM

pipe *D* to the nozzle *N* of the ejector *E*. The high velocity jet discharged by the nozzle *N*, entrains the oil from the reservoir *R* and discharges it through the pipe *F* to the pump *P* and to the bearings *G* from which the oil drains back to the reservoir.

Since the high pressure jet of an ejector is capable of entraining from one to three times its own volume of fluid and delivering it at some lower pressure, it is evident that a small part of the oil delivered by the pump *P* through the nozzle *N*, enables the ejector to entrain not only oil enough to supply the ejector with high-pressure oil, but also to supply sufficient additional oil to meet the requirements of governing and

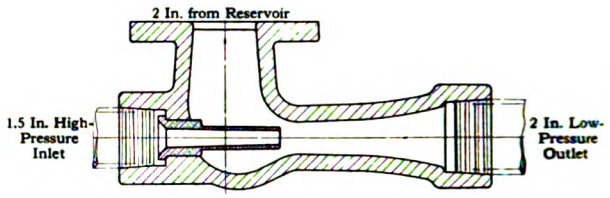


FIG. 19—AN EJECTOR FOR OIL GOVERNORS

those of the lubricating system. A pump *H* is shown connected to the reservoir *R* for delivering the oil through the check valve *K* and the pipe *L* to the suction of the pump *P* for starting.

To avoid an excessive demand on the ejector when the operating piston moves, the discharge from the operating cylinder is led directly to the impeller inlet, so the oil required to move the operating piston does not have to be supplied by the ejector, the load on which remains constant. This connection is not shown in the diagrammatic piping arrangement.

In this arrangement, it is seen that the ideal requirements for a perfect governing and lubricating system have been met. First, and most important, the governing device itself is mounted on and is a part of the main turbine shaft without the intervention of gears, links or moving parts. There are no sliding parts between the governor and the valve operating mechanism, the connection between the rotating and stationary parts being through the oil pumped by the impeller. The oil supply to the bearings and the pump is by means of a static device having no moving parts and absolutely nothing which will wear out or get out of order. The smallest opening in the ejector for a 500 kw turbine, Fig. 19, is 7/16 inches, which is large enough so that there is practically no danger of this becoming clogged unless rags or waste are left in the oil reservoir, but ample strainers with ¼ inch holes are provided around the ejector suction so that even these would not prevent the operation of the ejector.

As a matter of fact, up to the present, not a single failure of the ejector lubrication system, or oil governor has occurred in a total of over fifteen hundred turbine years operation.

*(To be Continued)*

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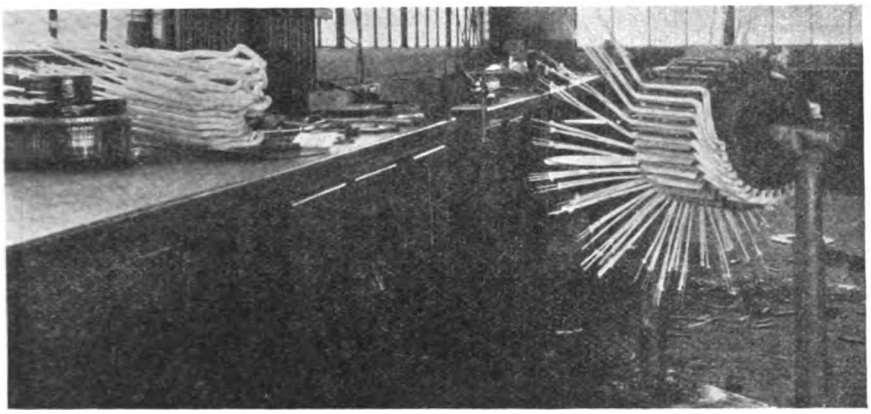
# Organized Maintenance of Electric Locomotives for Coal Mines



JOHN S. DEAN
Renewal Parts Engineer,
Westinghouse Electric & Mfg. Co.

THERE are approximately 15 000 electric locomotives for gathering and main haulage service in the soft coal mines of Pennsylvania, Ohio, Indiana, Illinois, Kentucky, Maryland, Virginia and West Virginia. The output of these mines depends largely upon the reliability of service obtained from these locomotives. Too much emphasis cannot be laid upon adequate maintenance and upkeep to minimize breakdowns and keep them in service as the occasion demands. The following outline of fundamental requirements will greatly assist operators to maintain their locomotives properly.

### ORGANIZATION

To keep down the expense and to turn out the maximum amount of work with the least number of men, the shop force in charge of the upkeep of the locomotive equipment should be thoroughly organized. Each group of men should be assigned certain duties for which they are held responsible by one man in charge. This will avoid duplication of work and confusion in carrying out orders and reporting trouble. In this way, the head of the organization can keep in close personal touch with all lines of his work through the directing heads of the various established departments.

### RECORDS

A definite method of keeping simple and accurate records of the locomotive equipment will assist the heads of departments in supervising the work. The value of such records is unquestionable, as they keep the management informed on the details of repairs, costs, etc., in maintaining locomotive equipment. These records include wheel and axle life, armature and locomotive failures, tonnage hauled by each locomotive, costs of locomotive repairs, locomotive upkeep per ton of coal produced, etc.

### SYSTEMATIC INSPECTION

Too much stress cannot be laid upon the importance of systematic inspection. If carried out regularly and systematically such a proceedure will tend to prevent failures and breakdowns in service, and be a great aid in getting out the maximum tonnage. A suggested schedule for inspection follows:—

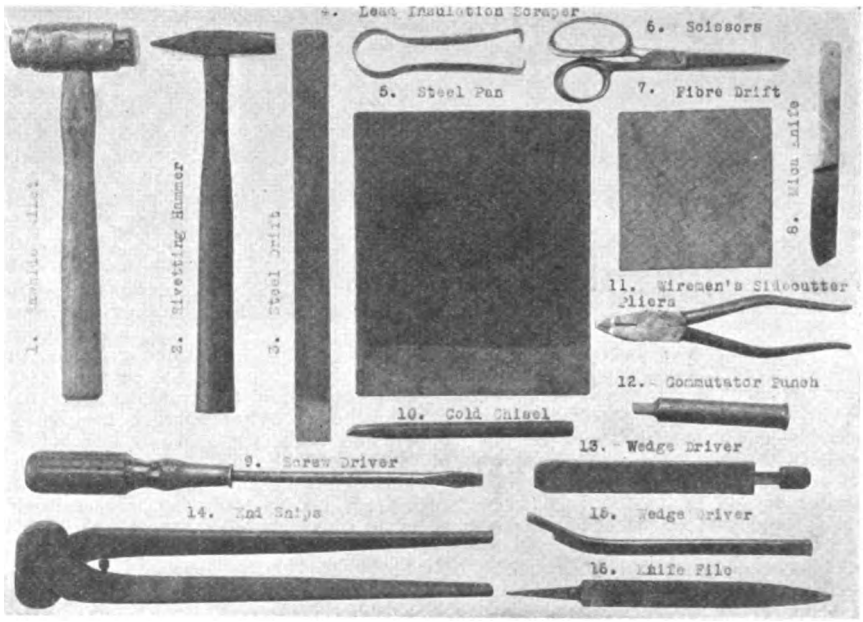



FIG. 1—ARMATURE WINDING TOOLS

*Daily Inspection*—Check brake rigging and examine shoes, tighten motor and axle cap bolts, inspect wiring, covers, head-lights, controllers, etc.

*Light Inspection*—Every thirty days tighten all bolts and adjust the brake rigging, examine the inside of the motors and carefully inspect the brushholders, commutators and carbons. Check the armature and axle bearing clearances, and see that the controller, head lights, wiring, and all mechanical parts are in good condition.

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*Heavy Overhauling*—Every eighteen months, take all of the equipment off of the locomotive and give it a general overhauling. Overhaul and put in good condition the journal boxes, brake rigging and all detail mechanical parts of the locomotives.

## MAINTENANCE

With a well-organized mechanical department, accurate records of locomotive troubles, etc., available for ready reference, and with all locomotives regularly and systematically inspected, the equipment can be cared for in the most efficient manner. As a further aid in handling this work, some of the details of the maintenance of mine locomotive motors will be outlined.

*The Shafts* of many mine locomotive motors are made from special axle steel. There are, however, a few of the more modern types of motors which use heat-treated axle or alloy steel to secure additional strength. In most cases of shaft replacements, standard axle steel should be satisfactory. However, where considerable trouble due to shaft breakage is experienced, it is advisable to use the higher grade heat-treated alloy-steel shafts to secure an additional factor of safety.

*Commutators*—In assembling commutators, care must be taken to keep all dust and moisture from the machined segments and the mica details, as carelessness may result in a

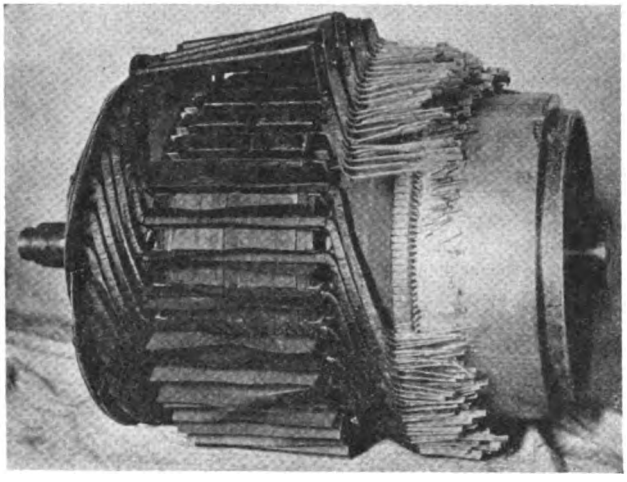

FIG. 2—A PARTIALLY WOUND ARMATURE

short-circuited or grounded commutator. It is important to use high grade mica cones and insulating bushings. After assembly clean out the vees on the copper and mica segments with fine sand paper. Thoroughly blow out all the dirt and dust and test for short-circuits. The assembled commutator should be heated to a temperature from 125 to 150 deg. C., and pressed while hot at from 20 to 30 tons depending upon its size. While hot and under pressure, the locking ring nut, or bolts should be drawn up tight.

The front "V" should be protected against dirt and oil by being given a smooth finish so it can readily be cleaned by wiping with a clean cloth. A layer of loosely woven, four-ply twine, well shellacked and smoothed with a hot soldering iron and then given several coats of a good grade of insulating varnish furnishes a solid, smooth protection at this point. It is advisable to round off the edges at both ends of the face of the commutator and to undercut the mica to a depth of from 1/32 to 3/64 inches. This must be carefully done, being sure that all small slivers of mica in the slots between the bars are removed. All repaired commutators should be tested as shown in Table II.

*Armature Winding*—The armature winder should be provided with the necessary tools such as rawhide mallet, steel and fibre drifts, screw drivers, pliers, scissors, etc., as shown in Fig. 1.

The most satisfactory results in rewinding armatures can be obtained only by using armature coils made from a good quality of copper, insulated with high-grade fibrous materials, or a combination of these materials with mica, and wound to the correct shape. If poorly shaped, the coils will not only be abused and damaged while winding, but they will take more time in winding. The insulation should be carefully reinforced at cross-overs and corners and the finished coils thoroughly treated by dipping and baking in a high grade insulating varnish.

All sharp corners and roughness in the slots that might damage the winding should be removed by filing or by a portable abrasive wheel. The insulating materials placed on the coil support should be evenly spaced to avoid any thin unprotected spots. The coils should be a snug fit in the slots, and wound so that the top of the coils extend about

TABLE I—AVERAGE STRENGTH AND COST OF AXLE STEELS

| Material | Relative Yield Point | Relative Cost |
|---|---|---|
| Axle steel | 100 percent | 100 percent |
| Axle steel, heat treated | 144 percent | 127 percent |
| Alloy steel, heat treated | 177 percent | 165 percent |

1/32 inch above the band grooves. This is essential to get a good tight banding job. In winding, the coils should not be twisted, bent or abused any more than necessary to get them in place. Insulating or protecting pieces should be placed at all points where coils or leads cross each other, as in Fig. 2, and where there is danger of short-circuiting. The correct winding information with a diagram of connections should be obtained from the manufacturer of the motors.

*Soldering*—In soldering the leads to the commutator, the soldering iron should preferably be held at the side of the commutator, as in Fig. 3, rather than on the top, and the pinion end of the armature should be raised about 6 or 8 inches. This proceedure tends to prevent the solder from running behind the necks and short-circuiting adjacent commutator bars. While soldering, do not use acid flux as this tends to weaken the insulating material on the coils. Rosin dissolved in alcohol gives good results. The best practice is to use a high percentage tin base solder for wire-wound jobs and pure strip tin on strap-wound armatures.

*Dipping and baking*—All rewound and repaired armatures should be partly banded, and then heated from 12 to 24 hours, depending upon their size, and dipped pinion end down in a good grade of black insulating varnish. After draining, they are baked at a temperature of from 95 to 105 deg. C. (200 to 220 deg. F.) for 48 to 72 hours depending upon their size. This treatment tends to fill all cracks and openings in the insulating material and greatly reduces the possibility of breakdowns which may be caused by moisture and other conducting materials filling these cracks. Further, this treatment acts as a bond to prevent vibration. The equipment necessary to handle this work is a tank for the varnish, a baking oven, preferably electrically heated and fitted with automatic temperature control, and the necessary apparatus to handle the armatures.

*Banding*—The most satisfactory results are obtained by banding the armature after it has been heated and the windings drawn down in place by means of temporary bands. A good grade of tinned steel banding wire ranging in size from No. 14 to No. 17, B. & S. gage should be used with tensions ranging from 100 to 300 pounds. A strip of tin plate placed under the core band tends to strengthen and make these bands less liable to work loose in service. All bands should be soldered with pure tin, as tin has a higher melting point than half-and-half solder. Thus it will stand a higher operating temperature before it will soften and give way under severe operating conditions.

*Testing*—During the process of rewinding, armatures should be given various tests, such as a ground test of 2000 volts, for 500 volt armatures, and 1000 volts for 250 volt armatures. This should be done after all coils are in place and the bottom leads connected to the commutator. The top leads should be lighted out to see that there are no crossed coils before connecting them to the commutator. Before final soldering, test for short and open circuits, using a testing yoke or a telephone receiver outfit. After soldering, the finished armatures should again be tested for grounds, open and short-circuits. Recommended ground tests for rewound and repaired armatures are given in Table III.

*Field Coils*—To insure the proper speed of the motor, the field coils must have the correct number of turns. The coils should be made from a good quality of copper of the proper size of wire or strap that will carry the current without overheating. They should have extra insulation at sharp corners and at the pole tips, and be so shaped that they can readily be assembled in place. When wound, all high-grade coils should be treated in a gum, using the vacuum high-pressure impregnating process. After this they are carefully insulated and then dipped in a high grade insulating varnish and baked. All coils should be given three such dipping and baking treat-

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ments. The finished coils are fitted with cable leads in preference to heavy brass terminals. The objection to these terminals is that they are likely to break off or develop loose connections and burn off the leads. Another objection is the difficulty of properly insulating them after the external connections are made.

*Field Windings*—When the field coils are mounted in the motor frame they should be spring supported to keep them tight on the poles to prevent vibration and chafing. The correct winding information, with a diagram of connections,

TABLE II—COMMUTATOR TEST VOLTAGES

| Operating Voltage | Test Between Bars | Final Test to Ground |
|---|---|---|
| 500 volts | 500 volts | 2000 volts |
| 250 volts | 250 volts | 1000 volts |

should be obtained from the motor manufacturer. As an additional factor of safety, it is advisable to check the polarity of both the main and commutating field coils after they are assembled in the motor frame.

*Brushholders*—To improve the operation of the brushholders, keep the porcelains clean, the shunts in good repair and the pressure finger mechanism working freely. The spring tension should be adjusted from 6 to 8 lbs. depending upon service conditions. Brushholders with a single carbon per holder are more likely to give trouble due to a low spring tension than those with two or more carbons. If, with the single carbon, it should jump from the surface of the commutator, the current is interrupted and the motor will tend to flash. Brushholders should be properly aligned on the neutral position, which is usually at the center line of the poles. They should be adjusted to about 1/8 inch from the surface of the commutator, and spaced around the commutator one-fourth the number of commutator bars, on all four-pole machines. The ratchet-type pressure fingers used on some of the older mine motors is being replaced by a more modern design known as the twin washer mechanism, which is simpler in construction and free from friction, as there are no rubbing surfaces in the operation of this mechanism.

*Carbon Brushes*—The use of high-grade carbon brushes on undercut commutators more than pay for themselves in increased life of the brush and the commutator, and further they improve the operation of the motors. When the commutators do not have the mica undercut a hard abrasive carbon brush must be used to keep the mica worn flush with the surface of the copper bars, otherwise high mica will develop and cause the motors to commutate poorly. Carbons should have a snug sliding fit in the boxes, and should not be copper plated, as this plating is liable to peel off and cause sticking of the carbons. Shunts on carbons are not usual on motors designed for 500 volt operation. They are generally used for motors operating on 250 volts, due to the heavier working currents.

*Housing or Frame Heads* must be kept tight in order to prevent the wear, not only of the housing, but on the frame at the housing seat. The clamping bolts holding the motor frame halves together must be drawn up securely as the clamping action of the frame, along with the bolts or dowels, prevents the housing from turning and working loose. Sometimes these parts work loose in service and as a temporary means of relief, shims are used to keep them in place. Best results are obtained by welding the worn seats on the motor frame, re-machining them to standard size, and then using new housings.

TABLE III—VOLTAGES FOR ARMATURE—GROUND TESTS

| Operating Voltage | Rewound Arm. | Repaired Arm. |
|---|---|---|
| 500 volts | 2000 volts | 1200 volts |
| 250 volts | 1000 volts | 600 volts |

*Heat-Treated Bolts*—Where trouble is experienced with motor frame and axle cap bolts working loose or breaking, some thought should be given to the use of special, high-grade, heat-treated bolts. Comparative tests show that a heat-treated axle-steel bolt has an elastic limit of more than double that of the standard hardware bolt. In general this type of bolt costs from two to three times as much as the standard hardware bolt, but experience has shown that it is good economy to use them, as they more than pay for themselves in reduced maintenance.

### ARMATURE BEARINGS

*The Sleeve Type* armature bearings used on a large number of mining locomotive motors should measure up to the following:—

1—Shells should be made from a good grade of bronze alloy.
2—Bore should have a smooth finish.
3—Bearing bore need not be tinned, nor lined with a babbit metal.
4—Oil grooves should be cut in the bore especially at the collar end.
5—Sides of the window should be chamfered.
6—Outside of shells should have a smooth machine finished surface.
7—Bearings should be given at least 0.006 in. initial clearance with the shaft.
8—They should be held preferably by a key in addition to a press fit of from two to five tons in the housings or heads.

*Ball and Roller Bearings*—A number of mine motors are fitted with ball bearings on the armature, and some use roller bearings. These bearings should measure up to the following:—

1—Balls or rollers and both races should be made from a high grade alloy steel, hardened.
2—The inner race should have a tight shrink fit on the shaft.
3—The outer race should ordinarily be a sucking fit in the bearing seat on the housing or head. In some cases the outer races are clamped in position.
4—The bearings must be carefully handled and kept free from dust, dirt and moisture, during storage and when being applied.

### AXLE BEARINGS

Axle bearings are of the sleeve type and made in two halves so they can be applied to the axle without removing the wheels. Modern practice for axle bearings is essentially similar to that outlined for armature bearings, except as necessitated by the fact that they are made in two halves. The initial bearing clearances should be at least 0.015 in. The half-shells should be held by dowels or keys, in addition to the clamping action of the axle caps.

FIG. 3—THE PROPER METHOD OF SOLDERING A COMMUTATOR

Some few of the older types of motors use malleable iron shells lined with babbitt metal and in some cases bronze shells are relined after being badly worn. Wherever possible these should be replaced by new bronze bearings.

### BABBITTING BEARINGS

Where it is found advisable to rebabbit bearings, the following points should be given consideration:—

1—Shells should be thoroughly cleaned.
2—Tin the shells in the bore before relining.
3—Use a high grade tin base babbitt metal.
4—Bearing shells and mandrels should be heated before rebabbitting.
5—Babbitt metal should be well stirred before pouring.
6—The babbitt metal should be poured while at a temperature of from 460 to 480 deg. C. (860 to 896 deg. F.)

Best results are obtained in babbitting by the use of pots heated by electricity and fitted with automatic temperature control to properly regulate the temperature of the metal while being poured.

### LUBRICATION

The practice of oiling locomotives on one large mining property are as follows:—

1—Journal and axle bearings are oiled every morning.
2—About one-half pt. of oil is used in each bearing.
3—A special black oil is used.
4—Ball bearings on the armatures are oiled once a week.
5—A special clear yellow oil is used on these bearings.
6—Controllers are greased every three or four days.
7—Trolley wheels are oiled every morning and in many cases several times during the day.

The above routine is fairly representative of present-day practice in connection with the lubrication of mine locomotives. However the following should also be considered:—

1—Use a good grade of long-strand, wool waste to pack sleeve-type bearings.

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2—Use a high-grade car oil, summer and winter grade.
3—Journal bearings, if properly packed with thoroughly saturated waste and protected from dirt and water, should not need any free oil.
4—Axle bearings, top feed, will require oiling every morning.
5—Axle bearings, oil and waste, side feed, if properly packed and protected from dirt and water, requires oiling every seven days.
6—Armature bearings, sleeve type, top feed, require oiling every morning.
7—Armature bearings, sleeve type, oil and waste, side feed, requires oiling only every seven days.
8—Lubricate armature ball bearings with an approved grease, and not with oil.
9—Ball bearings should be lubricated about every eight weeks if properly protected from dust and dirt.

It is a recognized fact that considerable damage is done to the commutators of mine locomotive motors by the use of too much oil in the commutator end armature bearing. This should be guarded against.

### PINIONS

To reduce trouble due to loose pinions, arrange to heat them in boiling water for about one hour, and while hot drive them on the shaft. A buffer made of soft metal should be held against the pinion to protect it while driving it on with a sledge. A suitable pinion puller should be used to remove worn and damaged pinions from the shafts. The use of the wedge and sledge method quite often damages the housing, bearing and shaft.

### ELECTRIC WELDING

Various worn and broken parts of the equipment on mine locomotives can be reclaimed with considerable saving of time and money by the use of electric welding. On the other hand there is a tendency to carry this practice too far by attempting to make repairs on some parts that are likely to break and give trouble in service. Some operators have attempted to build up worn bearing seats on the armature shafts of mine locomotive motors and after unsuccesful attempts have discontinued this practice. Welding of worn pinion key seats or damaged pinion nut threads on axle steel shafts has been successfully done. However, no welding of any kind should be done on shafts made from heat treated axle or alloy steel as this destroys the treatment of the material and will cause the shafts to fail in service.

The above outline covers the general factors in motor maintenance. Additional details will be suggested by the specific requirements of local conditions. A similar outline should be worked up by each operator in line with the suggestions of the locomotive manufacturer, for all of the other parts of the locomotive, such as controllers, fuses, circuit breakers, lightning arresters, resistors, trolleys, headlights, gathering reels, frames, wheels and axles, journal boxes and brake rigging.

In addition to maintaining the locomotive itself properly, the operation of mine locomotives will be improved and failures minimized, with a consequent larger output of coal, by adhering to the following additional suggestions:—

1—Keep the overhead trolley construction in good condition.
2—Provide and maintain a good road bed for the tracks.
3—All rails should be carefully aligned and secured to the ties.
4—Proper bonding of the rails is of the utmost importance.
5—Develop trained and experienced locomotive drivers or operators as they are a valuable asset to any mining company.

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# Graphical Flux Mapping

## III—Fields of Non-Salient Pole Synchronous Machines—(Cont'd)

J. F. CALVERT and A. M. HARRISON

In the first article of this series which appeared in the March issue of THE ELECTRIC JOURNAL, a fundamental principle for graphical flux mapping was given and a few simple applications were shown. The second article covered the flux distributions in turbine generators at no load.

THE point has been made, in connection with the drawings shown in the preceding sections, that it is far easier to draw a flux field if a similar figure is available for reference. It is the purpose of these articles to show a series of such typical solutions for various forms of commercial electrical apparatus. In the previous section, the drawings, with the exception of a few introductory figures, were all for the no-load flux fields of turbine generators when only the rotor winding was excited. In this section, the discussion of flux distributions in turbine generators will be continued with the case where only the armature is excited.

A point mentioned in the last article should be repeated, namely, that the effects of damping currents have not been considered. The fields have been drawn strictly on the basis of the magnetomotive-force sources shown in the drawings. The flux distributions in the rotor and stator iron will not be shown, because these can be estimated from the boundary conditions given in this article, and in accordance with the methods used for the no-load fields shown for these parts in the previous article.

When only the stator winding is carrying current, the tops of the stator and rotor teeth can be assigned numbers in a manner similar to the usual numerical designation for an air-gap m.m.f. wave. However, the difference in these numbers, as shown in Fig. 26, give the relative m.m.f.'s between the corresponding iron surfaces in the directions from the higher toward the lower numbers. This establishes the number of orthogonal lines in the gap, and the slots from which these lines emanate. The direction and relative magnitude of the currents in the armature conductors are shown in the figure by the numbers on the conductors. The positive sign indicates that the current is upward from the sheet and the negative sign shows that it is downward.

As stated, the numbers on the teeth give the number of orthogonal or ampere turn lines between the metal surfaces along the air-gap. Certain of these must meet iron surfaces as shown in the drawing. The method of laying out a singular point where an orthogonal line meets an iron surface, was described in the first article.

All the orthogonal, or m.m.f. lines, must emanate

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from the conductors shown. Certain of these lines turn from the air-gap into each slot, unless the m.m.f.'s in the slot completely cancel. In a two-layer winding, this occurs only when the currents in the two conductors in a slot are equal and opposite. However, the slots flux can always be mapped. The method of doing this for deep, rectangular slots, was discussed in some detail for three cases in the preceding article, and, therefore, the slot distributions are shown in Fig. 26 without further explanation.

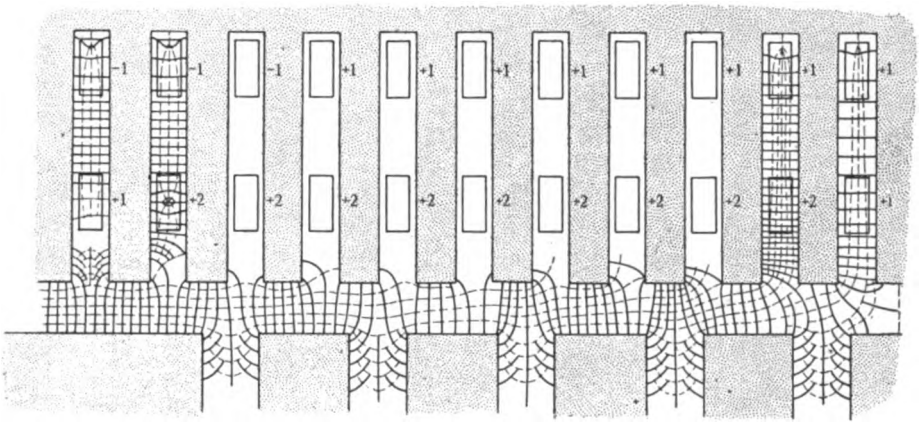

FIG. 26—AIR-GAP FLUX OF TURBINE GENERATOR WHEN ARMATURE ALONE IS EXCITED

### FLUX DISTRIBUTIONS IN THE END ZONES, ARMATURE ALONE EXCITED

The field in the end winding really imposes a three-dimensional condition, but on the basis of a fairly reasonable assumption, the magnetomotive force distribution may be viewed as a two-dimensional problem. The assumption to be made, is that the flux passes perpendicularly through the end winding surface. This has been checked in machines having two-layer conical windings, and found to be practically correct.

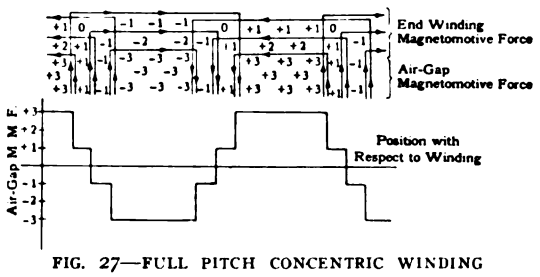


FIG. 27—FULL PITCH CONCENTRIC WINDING

Currents of equal magnitude in both windings and with directions indicated by arrows. Numbers and signs indicate the relative magnitudes and directions of magnetomotive forces perpendicular to the surface through all the windings, on the assumption that the flux passes perpendicularly through that surface.

On this basis, the end zone may be thought of as an irregularly shaped projection of the air-gap. The usual method of showing winding m.m.f.'s of the gap may be applied to the end winding zone, and the m.m.f.'s in the latter space established. This is shown in Fig. 27 by a simple concentric winding with equal currents in all conductors. The m.m.f.'s applied between the various conductors along the air-gap are shown in the usual manner. Positive values of m.m.f. indicate that the flux direction is upward; negative, downward. Along the air-gap, if one could move a unit pole outside of a coil, the effect of the m.m.f. of that coil would be lost. Moving into another coil, the effect of the m.m.f. of the latter coil would be gained. The same argument has been applied in the end windings. The m.m.f.'s shown in those spaces are the total values per pole for the corresponding flux tubes. This is true, because the flux lines pass perpendicularly through the end winding surface and do not cross. The flux tubes may diverge or converge after passing through the winding, without changing this theory.

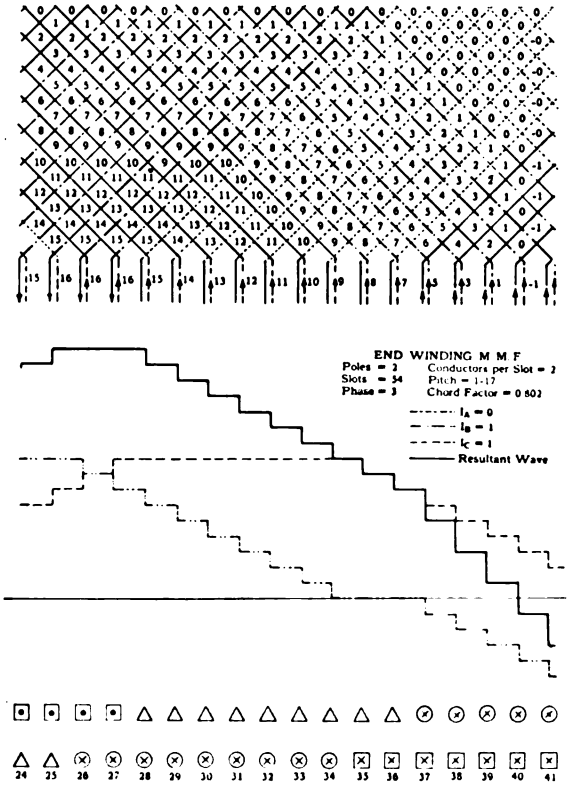


FIG. 28—END WINDING M.M.F., ONLY TWO PHASES EXCITED

To simplify the conception of these paths, the three-dimensional field may be replaced by another in which the flux passes perpendicularly through a flat end winding. The paths through each of the spaces

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between coil sides can be thought of as a group of short vertical shafts, each of the same cross section, but with their lengths proportional to the respective reluctances of the true flux tubes (which have varying widths.) This imaginary condition can not be produced in reality, but it gives a simple graphic view of the m.m.f.'s and reluctances at one instant of time, which is of some value in picturing a complicated problem.

Three-phase chorded diamond winding for two different sets of instantaneous current values are shown in Figs. 28 and 29. It should be noticed that when only two phases are excited, as in Fig. 28, there

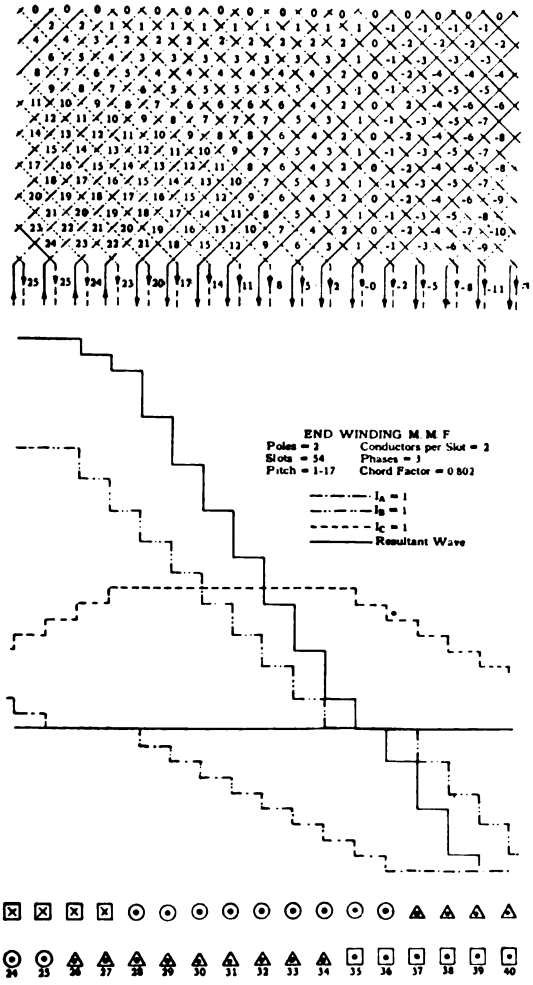


FIG. 29—END WINDING M.M.F., ALL THREE PHASES EXCITED

is a section in the outer part of the winding, with no m.m.f. through the conical section, which must have flux coming into this V-shaped part from the remainder of the winding, but which is not present for other instantaneous values of current. This V-section increases in size with short chording.

This theory concerning the end winding m.m.f.'s must be applied with some care. The entire winding should be excited and should be balanced in each pair of poles to validate this sort of a picture. The end bell flux due to the armature end winding may be plotted as in Fig. 30, in the stator pole center plane, where the field remains practically in one plane. Certain assumptions have been made to assist in the plotting of this approximate field, namely:—

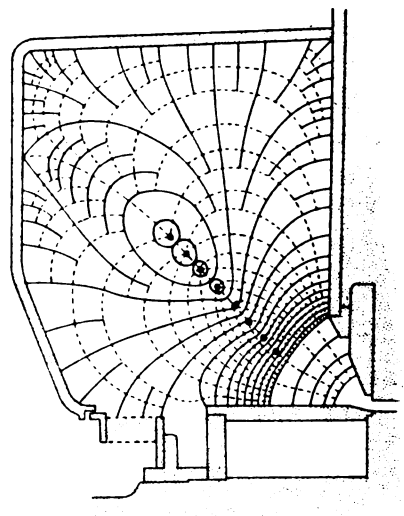

FIG. 30—END BELL FLUX DUE TO END WINDING

*a*—Uniform thickness of the incremental section perpendicular to the sheet.
*b*—Infinite permeability in the iron.
*c*—An equivalent single layer winding having practically the same m.m.f. distribution, and half as many conductors as the two-layer winding, which has been replaced.

The number of orthogonal lines emanating from these conductors is proportional to the current per conductor, and these lines must pass through the air-gap to the corresponding conductors on the other end, as a brief consideration of the main magnetic circuit will show. In plotting this field, it is best to start near the air-gap and proceed outward. The correct total number of ampere-turn lines are started outward from the

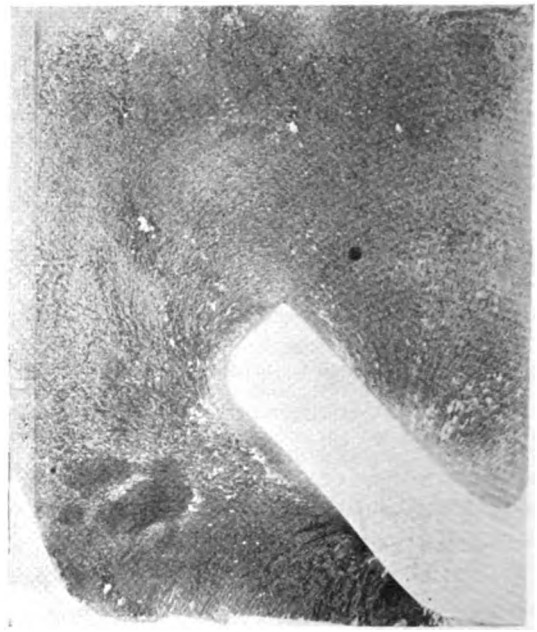

FIG. 31—AN IRON FILING PICTURE OF THE FLUX CONDITION OF FIG. 30

gap and the proper number are dropped off as the conductors are reached. These lines are drawn so the flux passes nearly perpendicularly through the end winding.

It is worth while to note that the flux distribution

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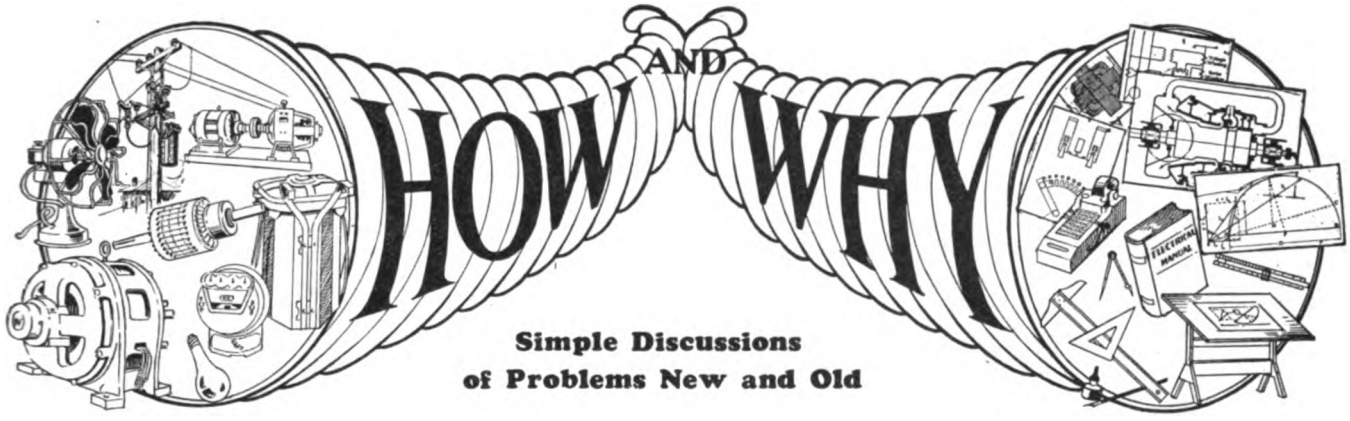
in the end bell iron is influenced by a number of factors which cause irregularly shaped fields at various instants of time, when the armature is excited alone. However, these will not be taken up here.

The flux distribution in the retaining ring is not sufficient to produce saturation, and discussion of this field will be omitted.

*(To be Continued)*




## Overloads on Current Transformers

CURRENT transformers, when subjected to short-circuits, may fail for either of two reasons;—the heat generated in the winding may be sufficient to destroy the insulation; or the mechanical force generated by the short-circuit current may be large enough to damage the coils, if

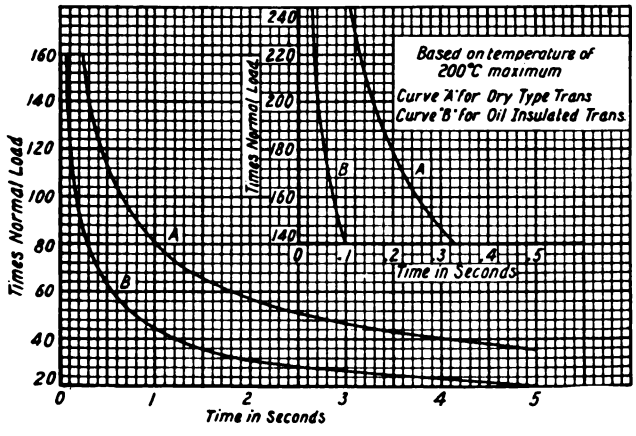



FIG. 1—TIME REQUIRED TO HEAT THE TRANSFORMER TO ITS MAXIMUM SAFE TEMPERATURE

the transformer is of the wound type. The curves in Fig. 1 show the thermal capacity of typical dry and oil insulated current transformers. For example, a typical dry-type current transformer will carry fifty times its rated current for 25 seconds.

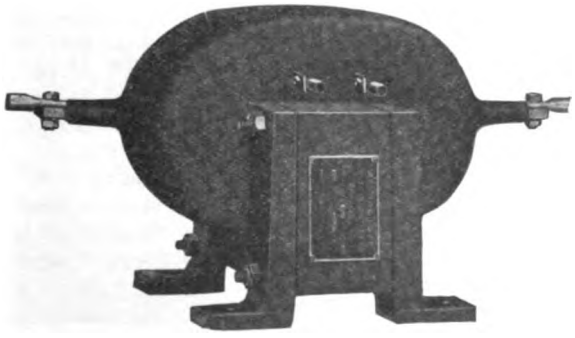


FIG. 2—A DRY-TYPE CURRENT TRANSFORMER

Dry, wound-type transformers, of the type shown in Fig. 2, will mechanically stand short-circuits whose sustained r.m.s. value is fifty times the rated current of the transformer. Special bracing can be put on such transformers to make them mechanically good for 150 times their rated current. The curve in Fig. 1 shows that with this current they will reach their thermal limit in 0.29 seconds.

Mechanically, the through or ring-type current transformers cannot be destroyed by short-circuit forces. The current capacity then is limited only by the thermal capacity of the windings.

## Now it's Radio for Locomotives

RADIO sets are being added to the ever increasing list of freight-locomotive appurtenances. Radio is, of course, not for the entertainment of the train crew but for the practical and important purpose of providing communication between the engine and the rear end of the train. Experiments with radio communication between locomotive cab and caboose which have been in progress for several months on long freight trains on the James River subdivision of the Chesapeake & Ohio Railway are proving very successful.

This subdivision is in a mountainous region where ordinary signaling is very difficult, and is a good proving ground for radio signaling. The course has many curves and several bridges and tunnels and is so tortuous that engine and caboose are rarely in sight of each other and are often on opposite sides of a mountain. Signaling by hand or lantern is generally out of the question. Trainmen usually have to walk within signaling distance in order to enable trains to make the proper movements, and since the trains are upwards of a mile long, much time is lost by this process, and a delay anywhere along the line upsets schedules for the whole subdivision. The use of radio signaling between engine and caboose completely obviates this trouble and greatly shortens the running time of the train.

For example, on a recent run with 90 cars of coal, a brakeman on a passing train signaled to the caboose of the radio-equipped train that a brake was sticking near the center of the train. The engineman was notified by radio and he slowed down to let the head brakeman off. The brakeman located the sticking brake, released it, and hopped on the caboose, all without completely stopping the train. The engineman was then notified by radio to proceed.

Shortly after this the train broke in two just ahead of the caboose. Emergency brakes stopped the train, but the engineman was instructed by radio from the caboose to proceed to the nearest yards with the forward part of the train. On arriving at the yard, the defective car which caused the trouble was cut out, and the train's engineman was instructed

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by radio to come back, pick up the remaining cars, and proceed.

Several hours of time and possible damage to equipment were saved on both of these occasions and, on almost every trip, operation is facilitated by the radio equipment. When orders not requiring the signatures of the crew are missed by either end of the train, the crew receiving them transmits them to the other. In event of thick fog or heavy snowstorms, when visual signals are useless for distances of more than a few feet, the radio communication system is invaluable.

So much time is saved in these and other ways that a considerable fuel saving per trip is shown, not only by the train equipped with radio, but by all trains whose movement is dependent on the radio-equipped train.

The radio equipment consists of transmitters and receivers with loudspeakers, mounted in the engine cab and in the caboose. Signals are used for calling, and complete oral intercommunication is maintained on the entire trip. Clear loudspeaker volume is normally maintained, though there is a little, but not serious, fading when passing under trussed steel bridges. In tunnels between high bridges, beside high cliffs and in deep cuts, fading is more pronounced, though communication is always maintained by means of head phones. It is, however, not difficult to correct this trouble at the points where it is serious. The range of the system is several miles so that even the parting of the train does not cut communication.

On each train two 50 watt transmitters, operating on wave lengths from 90 to 130 meters, are used. The engine transmitter operates on 112 meters and the caboose transmitter on 120 meters. Receivers employing three stages of audio frequency are used. Power is supplied by a 24 volt, 150 ampere-hour storage battery. Plate voltage for the transmitter is furnished by a 24 volt to 1200 volt dynamotor. The antennae are of the loop types and are connected to the transmitters by double-braided, rubber covered, high-voltage wire to reduce outside absorption.

## How to Clean Grease and Oil from Windings

THE windings of electrical apparatus, in certain classes of service, become covered with oil or grease, due to the presence of oil vapor, or in the older types of motors from direct leakage of oil from bearings. The bearings of modern motors are practically free from leakage. Oil resisting varnishes have been perfected which reduce to a negligible extent direct injury to the windings from the oil. However, an accumulation of oil is sometimes unavoidable and if permitted to remain it may prove harmful, due to the fact that it will collect conducting dirt which, eventually, will be carried to all parts of the winding. For this reason, it is desirable to clean any accumulation of oil or grease from the windings of such apparatus at intervals. The time between cleanings will vary under different conditions.

In general there are three types of grease solvents which may be used for cleaning the insulated windings of electrical apparatus:—

1—Benzine or gasoline.
2—Carbon tetrachloride.
3—A mixture of gasoline or benzine and carbon tetrachloride.

Either benzine or gasoline is very inflammable, and their vapors quite explosive when mixed with the proper percentage of air. If this type of solvent is used, there should be good ventilation and minimum fire risk. Care should be taken to prevent the workers' clothes from becoming saturated with the solvent; if the clothes should become saturated, they should be removed before leaving the work.

Benzine or gasoline have the least corrosive action on the insulating varnishes and where conditions permit should, therefore, be used in preference to the other solvents.

Carbon tetrachloride is non-inflammable and non-explosive. It has a slight toxic effect which, however, is not cumulative. This solvent is much more corrosive in its action than either benzine or gasoline. As it is a solvent of rubber, it should not be used on any parts where rubber insulation is used, such as the leads coming out of the motor. Also care must be taken to protect adjacent parts from corrosion. With these precautions, carbon tetrachloride, which evaporates quickly, may be used for cleaning windings with small risk of damage. It should be used where proper ventilation is not obtainable or where fire risk is high.

A mixture of 50 percent carbon tetrachloride and 50 percent benzine or 60 percent carbon tetrachloride and 40 percent gasoline is non-inflammable but the vapors mixed with the proper amount of air are explosive. If there is sufficient ventilation so that explosive fumes will not accumulate, this solvent may be used where there is fire risk. There is no particular danger from spilling these mixtures on the clothing.

With a dry cloth or waste, wipe from the windings as much of the oil or grease as possible. Clean the windings with a rag or waste moistened with one of the above solvents. In order to reach inaccessible parts of the windings, a spray may be used with sufficient force to wash the oil away. Also, a swab moistened with the solvent may be used with good effect.

As far as possible, all parts cleaned should be dried with clean waste or rags and the apparatus given an opportunity to dry out thoroughly before being placed in service.

If the varnish coating of the windings shows considerable deterioration, the windings should be retreated with an an oil resisting varnish.

## The Depth of Flutes in Transformer Cases

THE usual ratio of flute depth to flute width of a self-cooled transformer is about two to one. The reasons for this illustrate, simply, the principle of balance and compromise which pervades all the work and problems of the engineer.

The purpose of the flutes it to increase the heat dissipating ability of the transformer. A transformer gets rid of the most of its heat by two methods—by radiation and by convection. The amount of radiation is dependent on the circumference of the tank, that is, the projected area. Hence, increasing the corrugation depth would increase the heat radiating qualities but little. However, the heat eliminated by convection depends upon the total transformer surface, that is, the developed surface. The deeper the flutes, the more the convection surface. However, as the flutes become deeper the circulation of cooling air on the outside and of the heated oil on the inside becomes poorer. Thus, the self-cooling ability does not increase in proportion to flute depth.

The flutes of the transformer case give strength and stiffness to the transformer. Up to a certain point, the deeper the flutes the stiffer the structure. This is another factor urging increase of the depth to width ratio.

A transformer case is made by corrugating a flat piece of sheet steel in a pressing machine and then bending it into its rectangular shape. The deeper the corrugations or flutes, the greater the pressing difficulties and, consequently, greater cost of the finished product. This is a factor tending to lower the flute ratio.

This polygon of forces, so to speak, results in a compromise flute ratio of two to one as the most satisfactory one for the average transformer case.

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# Ventilation of Railway Motors

F. PAULSEN

NATURE and the needs of man have imposed many hardships on the railway motor. The greater part of such breakdowns as occur are attributed to the elements, and the demands on the part of operators and the public for cheaper, stronger, lighter and smaller motors have given the designer problems which are difficult to solve. Not the least among these has been the problem of providing cooling air, yet keeping the weather out. Rain may reach the motors

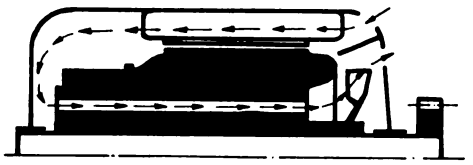

FIG. 1—AIR PATHS IN A SERIES VENTILATED MOTOR

directly in strong winds, or muddy water be splashed into them by the wheels. Snow is blown about more easily than rain, and the accompanying cold weather may cause trouble from the water that results from melting the snow inside the motor. Sand and dust have a large share in the wear of brushes and the accumulation of heat-insulating coatings on the windings, while the call for lighter and smaller motors has limited the thermal capacity.

While the removal of heat from the motor is the prime object of ventilation, proper ventilation should take care of the dust, dirt and moisture which are destructive. Enclosed motors using a circulatory ventilation sometimes give trouble from surface leakage when brush and commutator dust deposits itself on the windings behind the commutator. When the ventilated motors came into existence, trouble continued through the deposition of dust and sand on the brush-holder mechanism. In this case, the wear of the carbon brushes was first attributed to sparking between the brush and the holder. Later, the true cause was found to be the entrance of abrasive sand into the brush-holder mechanism. The passage of cooling air is not the whole problem of ventilation. Air can be passed through readily enough, but it must follow such a path that the destructive elements can do no damage.

The first railway motors were almost completely open. Insulation at that time was not developed to withstand the service nor was the commutator properly protected. It was soon evident that non-ventilated motors must be used. Non-ventilated motors could be used to some extent at first because of the bulk of material in them, and the resultant thermal capacity. However, space limitations became a prominent issue, so that it became necessary to resort to some means whereby the heat could be carried from the windings more readily. The armature core was opened and

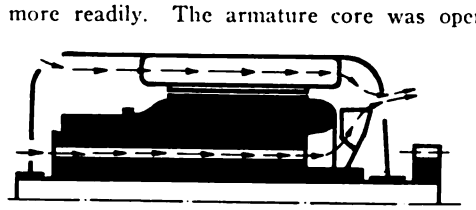

FIG. 2—AIR PATHS IN A PARALLEL VENTILATED MOTOR

radial holes added in order to provide a circulation of air within the motor, the air carrying the heat from the warm sections to the cooler sections, thus making use of the whole motor for heat dissipation. As motors became smaller this method proved insufficient and it became necessary to force air through the motor to help in the disposal of the heat.

A fan was placed on the shaft of the motor to cause the draft of air, and a question arose as to the best way to direct the air. Two general schemes have been used; namely, series ventilation and parallel ventilation. Series ventilation, shown in Fig. 1, takes the air in, as a rule on the pionion side, passes it across the field poles and returns it through the armature to the exit at the pinion end. This path is made possible by the use of baffles. Parallel ventilation, shown in Fig. 2, makes use of a divided stream of air drawn in at the commutator end and discharged at the pinion end.

Advantages are claimed for both systems. Both the field and the armature are furnished with cool air in the parallel type; whereas, in the series type, the armature is furnished with air already heated by the field. With the same fan equipment less air is furnished to the series ventilated motor. This means that less dirt is carried into the motor by the ventilating air. Part of the dirt that is carried in is thrown out of the air stream before reaching the commutator. This is one of the main reasons for the smaller amount of brush wear in series ventilated motors. To keep dirt from the commutator zone of a parallel ventilated motor was a problem that has been largely solved by what is known as dual ventilation. This type of ventilation, shown in Fig. 3, has the commutator zone baffled off and the air drawn in at two points, one at a point on the frame on the commutator side of the field coils, and the other near the center of the housing on the commutator end, the air of each stream passing to the pinion end and out. The air is not drawn over the commutator and therefore deposits no dirt and dust on it. The commutator has its heat removed by the air stream which passes through the armature.

Light-traction motors have not used forced ventilation by separately driven blower to any extent, because there is no room on small cars for blowers and ducts.

Ventilated motors are often made inoperative in winter because of slush and snow. Troubles of this kind can be

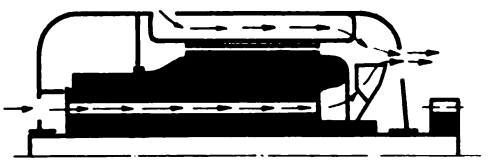

FIG. 3—AIR PATHS IN A DUAL VENTILATED MOTOR

avoided by more careful attention to the use of solid covers. During cold weather there is not the great need for ventilation as in summer, so that solid covers can be used without running the motor temperature beyond safe limits. While solid covers may not be a perfect solution, their use has been generally very effective. With solid covers on, the motor is really operating totally enclosed and a certain amount of moisture will collect in the motor. Drains are now put in the bottom of the frame to drain this moisture. In the winter time these drain holes are apt to become frozen over and precaution should be taken to see that these are opened at regular inspections.

The advantages gained from better ventilation can be shown readily by the difference in motor weights. For the same continuous ampere rating, ventilated motors are approximately 60 percent as heavy as non-ventilated, and for the same one-hour horse-power rating they are approximately 85 percent as heavy. The continuous rating has increased from about 50 percent to 75 percent of the one-hour rating because of the bettered ventilation.

The smaller diameter armatures leave little room for an air stream, and the longer core and field have added to the resistance of the air stream. By making smooth passages of uniform cross-section, with no corners for eddy currents of air, the resistance may be kept down. A careful survey of the design will indicate how the ventilation may be secured most efficiently from a mechanical and a cost standpoint.

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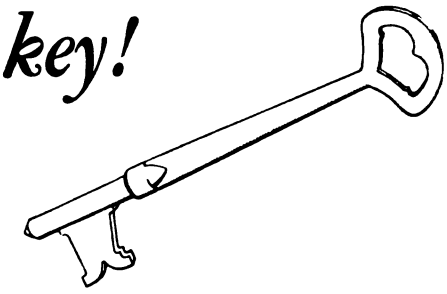

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In January, 1920, a new 30,000-kw. unit was to be installed. A meeting was called. A technical representative of the Vacuum Oil Company was invited. On this new unit they decided to use Gargoyle D.T.E. Oil Light.

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# The JOURNAL QUESTION BOX

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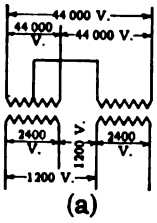
To receive prompt attention a self-addressed, stamped envelop should accompany each query. All data necessary for a complete understanding of the problem should be furnished. A personal reply is mailed to each questioner as soon as the necessary information is available; however, as each question is answered by an expert and checked by at least two others, a reasonable length of time should be allowed before expecting a reply.

2826—CAPACITY CURRENT—1—Should there be capacity current between the windings and the core of a 75 kv-a distributed core transformer? In the case of several local transformers of this size a small, but visible, spark is apparent when the ground on the case is removed. A megger test with a 500 volt megger shows infinite insulation. With 2000 volts, 60 cycles applied between the core and one of the windings there is a spark of fair magnitude. b—Our incoming power line is three-phase 44 000 volts. It is understood it is connected star at the power house with the neutral grounded. It feeds a bank of transformers Scott connected for transformation from 44 000 three-phase to 2400 two-phase.



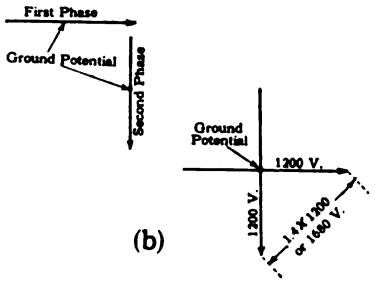




FIG. 2826

Will you please show vectorialy why there should be a voltage of approximately 1200 volts between the leads of opposite phases as shown in Fig. (a). P. T. (HAWAIIAN ISLANDS)

1—The windings, magnetic circuit and core of a transformer, together with the ground, form the plates of a condenser. When the ground on the core is removed, the core immediately assumes a potential above ground. This potential across the gap formed in removing the ground produces a visible spark. The same spark would also appear when the ground connection is made to the case. We assume that the megger test referred to is made between the winding and the ground, although we do not see what relation this has to the discharge from core to ground. It is to be expected that the application of 2000 volts between windings and ground would give a fair spark when the contact is made or broken. The windings and the core here form the two plates of a condenser, and the spark is the evidence of discharging current flowing. 2—If the two low voltage winding of the transformer group are without grounds the middle points of each winding are at approximately ground potential. They therefore assume the vector positions shown in the Fig. (b), that is the middle points of each winding come to a common point. Therefore between the free terminals there will be a voltage of 1/4 × 1200 or 1680 volts. Since the middle points of the windings are not tied together electrically, very little current can be delivered at this voltage. When any considerable current is drawn, this tends to bring the two terminals closer together as regards potential. With the instrument used for this measurement, this voltage was reduced from 1680 to 1200 volts. The condition establishing the e.m.f. between the windings is electrostatic.

E. G. R.

2827—MERZ-PRICE TRANSFORMER PROTECTION—What precautions should be taken to ensure the successful application of the Merz-Price protection as applied to power transformers? The transformer in question 6000 volts delta; 110 000 volts star; with the neutral directly grounded feeding over head transmission lines. The transformer is not protected for overload. In case of line trouble will the unbalanced current be liable to cause the Merz-Price protection to trip, if so what must be done to prevent this possibility? The transformer is fed from a generator of the same capacity and protected by the Merz-Price protection.

C. R. (NOVA SCOTIA)

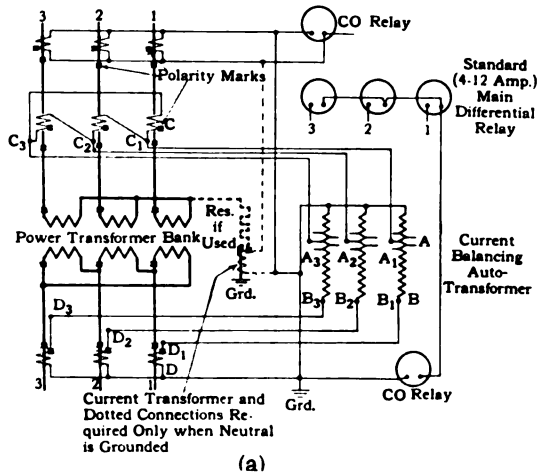



FIG. 2827

The Merz-Price protection, which is probably better known simply as *differential protection*, cannot be set to offer as sensitive protection when applied to transformer banks as when applied to generators or buses. This is due to the fact that the transformer magnetizing current appears only in the side which acts for the time as the primary, and under changing voltage conditions may reach and exceed full load magnitude for a few cycles. Moreover, the current transformers on the high tension side usually have quite different ratio and phase angle characteristics from those on the low tension side with the result that under varying transformer loads, the secondary currents of the current transformers no longer accurately follow the currents in their primaries. This is particularly true for short circuits external to the transformer. In applying differential protection to transformer banks precautions must be taken *first* that the connections are properly made, *second*, that the protective relays are properly set. Fig. (a) shows the connections for the differential protection of a star-delta transformer bank. Particular attention should be given to determining corresponding primary and secondary leads of the same instantaneous polarity and to see that leads from one phase are not interchanged with leads from another. It should be noted too that the current transformers used for differential protection around a star-delta transformer bank are connected just the reverse of the power transformer bank so that the current transformer secondary currents from the high tension and low tension sides of the bank may be in the same time phase relation. That is, the current transformers designated at *C*, which are on the star side of the bank, are themselves connected delta, while the current transformer designated as *D* on the delta side of the bank are themselves connected star. Since the current transformers *C* are connected in delta, the leads from *C* to *A* normally carry 1.73 times the current in the *C* current transformer secondaries. On the other hand, the leads from *D* to *B* carry the same current as the *D* current transformer secondaries. In order, therefore, to secure a balance between the current in the leads *CA* and *DB* they must be connected through an auto-transformer in such a way that the turns from *A* to ground and from *B* to ground are in the inverse ratio of the currents in *CA* and *DB*. The three main differential relays are connected between each of these balanced phase circuits and ground, there being a choice of four positions in which to make this

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connection. As to whether the main differential relays should be supplemented by the use of ground relays must be determined by the system connections and the degree of protection desired against ground faults; remembering that ground faults may involve considerable resistance which may limit the current to the extent that the regular differential relays cannot function. In the problem at hand, it is not likely that the generator neutral is grounded so that the delta-side ground relay is not required. Since the star-side of the transformer bank is solidly grounded the star-side ground relay should be considered and the extra protection gained weighed against the cost of the additional relay and the current transformers. In this connection it should be remembered that if a ground fault occurs near the neutral that but little fault current will flow through current transformers *C* and *D* as the faulty winding acts as an auto-transformer having as well a tertiary composed of the delta side of the power transformer. For such a fault the neutral current transformer will carry sonsiderable current which will function the star-side ground relay.

As previously mentioned precaution must be taken in setting the differential relays as magnetizing current surges cannot be balanced out and as the current transformers may not hold true ratio and phase performance. Although the magnetizing current surges may reach and even exceed full load current, they are of short durattion so that by giving the main differenttial relays a time setting of at least 0.2 seconds definite minimum no trouble from this respect should be anticipated. To determine the current setting of these relays one must consider the worst fault outside of the transformer and determine the unbalance current which results from such a fault. This, therefore, presupposes a knowledge of the worst short circuit current and the performance of the current transformers for this primary current and also a knowledge of the burden carried by these current transformers which includes the secondary wiring, auto-transformers, and relays. Since no information was given regarding the size of the banks or current transformers no definite answer for the particular problem can be given. Experience though shows that the main differential relays could not be set for less than full load which usually corresponds to about four amperes secondary current, and if low ratio bushing type current transformers are used on the high tension side with wound primary current transformers on the low tension side their setting may have to be as high as three times full load or about 12 amperes secondary current. The star-side ground relay is not affected by magnetizing current and hence can be given a very short time setting. Its current setting will depend upon the maximum secondary current unbalance resulting from an external ground fault due to the characteristics of the current transformers in the line not matching those of the current transformer in the transformer bank neutral. The neutral current transformer should, therefore, be carefully chosen with respect to the current transformers on the high tension side.

Summarizing, therefore, to prevent through short-circuits from functioning the overcurrent differential relays, the connections must be correct and the relays set higher in current than the unbalanced current resulting from differences in the current transformers for the most severe external short cuircuit and longer in time than the worst magnetizing current surge exceeds the current setting of the relay. E. H. K.

2828—TRANSFORMERS IN PARALLEL—We have two units, each composed of a generator and a bank of delta-delta connected transformers, connected as shown in Fig. (a) the

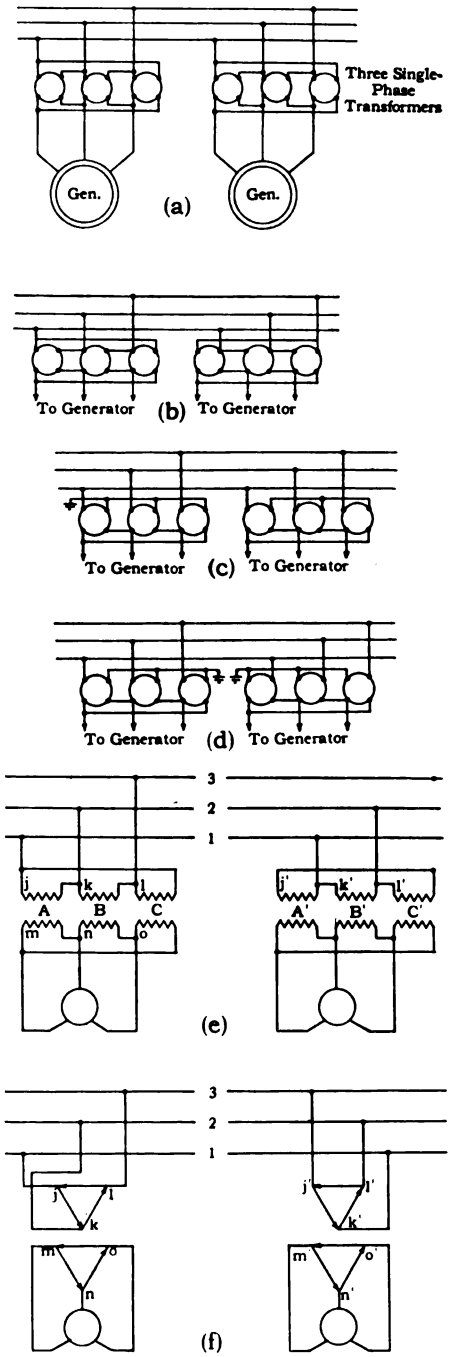


FIG. 2828 (a, b, c, d, e and f)

two units being paralleled on high tension side. Suppose that one unit has been disconnected from the bus and when reconnected to bus instead of being put back as in Fig. (a) is put back as in Fig. (b). 1—What would be the effect of the change as regards the operation of the unit? 2—Would such a change necessitate a change in any of the "small wiring" of the unit such as differential relays, synchroscope connections, meters, etc. 3—Please give a vector representation of the two conditions? 4—Although in both cases the units are delta-delta connected how may we designate the one in distinction from the other? 5—Will you discuss a similar case regarding delta-star units as in Figs. (c) and (d).

C. S. (CANADA)

The two groups of transformers are connected the same on both the primary and secondary sides in (a) hence the phase relationships are correct. In (b) the right hand group has the secondary leads brought off from dif-

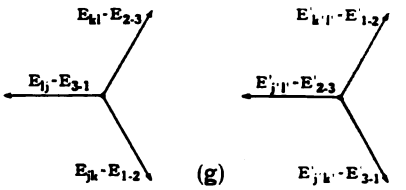


FIG. 2828 (g)

ferent phases on the secondary side For example, from the group on the left the secondary of transformer (*A*) is connected to lines 1-2. The secondary of transformer *B'* on the right is connected to the same lines. The secondaries of transformer *A* and *B'* are evidently from Figs. (f) and (g) not in phase with each other. The connection is, therefore, not operative. That these voltages are not in phase may easily be shown as follows. The schematic diagram for Fig. (e) or Fig. (b) is shown in Fig. (f). The vector diagram for the condition shown in Fig. (f) is shown in Fig. (g). It will be seen that $E_{1\text{-}2}$ and $E'_{1\text{-}2}$ are 120 degrees out of phase and hence cannot be connected together. This is also true of $E_{2\text{-}3}$ and $E'_{2\text{-}3}$, $E_{3\text{-}1}$ and $E'_{3\text{-}1}$. The same general reasoning applies to the star connection which can be worked out in detail in the general line of reasoning as indicated above.

E. G. R.

2829—ELIMINATION OF RADIO INTERFERENCE—Please send information on how to eliminate radio interference caused by a violet ray machine.

C. D. S. (OKLA.)

It is a difficult matter to eliminate entirely radio interference caused by a violet-ray machine. A filter which consists of two choke coils of fifty turns each wound on a three inch tube is shown in Fig (a). Four condensers are shown of two microfarads each. Sometimes a complete filter is not required but two condensers across the line with

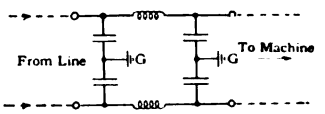


FIG. 2829 (a)

the middle point grounded is sufficient. In other cases the choke alone is sufficient to prevent the disturbance from being propagated. The interference caused by the machine is fed back on the local distribution system and usually annoys neighbors who are connected to the same secondary distribution network in the vicinity. Little direct radiation from the machine is experienced, and this can largely be avoided by placing copper shields around the gap of the spark knobs. L. A. T.

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# THE ELECTRIC JOURNAL

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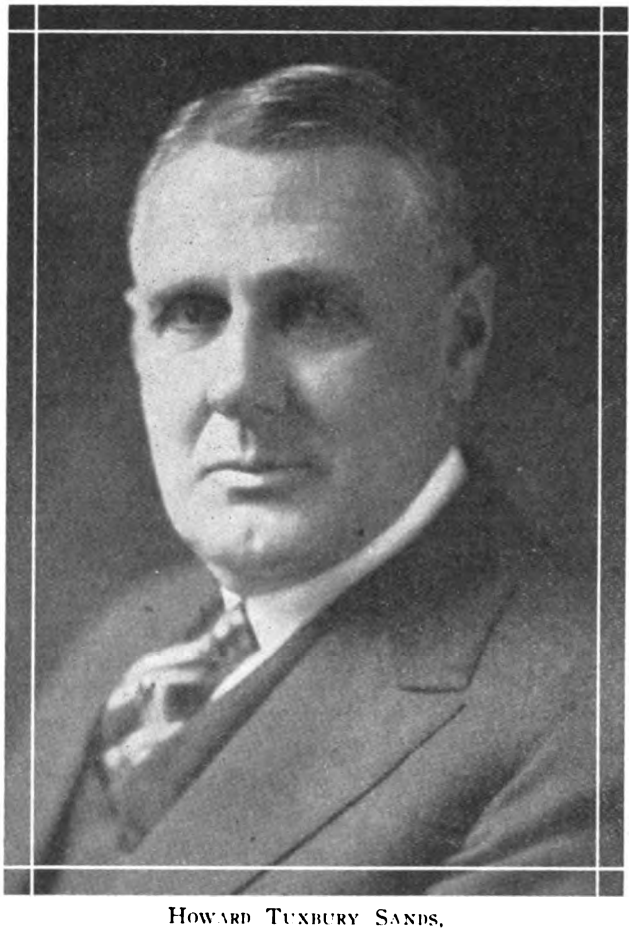
## Strive for Higher Standards of Public Service

H. T. SANDS
President, National Electric Light Association

NOT only are the electric light and power companies of the country constantly striving for higher standards of public service but they realize how essential it is that public understanding of these utilities shall not fall too far behind the growth of the industry.

The twelve-month period being brought to a close with the fifty-first convention of the National Electric Light Association has shown the industry to be increasing its contributions to the social and economic life of the country. The household consumption curve is steadily rising. It is estimated that the average home in the United States consumed five percent more electricity in 1927 than in 1926 and for this same period the average household bill for electric light and power increased only about two percent. During 1927 the average cost per kilowatt-hour for domestic consumers decreased from seven cents to six and three-fourth cents. This is incontrovertible evidence of the calibre of the service that the electric companies are giving to the country. These trends towards improved service and lower rates are continuing and it is apparent that the domestic load will become heavier as widespread appreciation of the advantages of home electrification is fostered by electric light and power companies, manufacturers, contractors, jobbers and dealers.



HOWARD TUXBURY SANDS,
Vice-President, Electric Bond & Share Co.

The amount of electricity employed in industry is dependent on industrial activity. For the first months of 1928, this showed a diminution in some parts of the country but, in many sections, manufacturing is now consuming more power. Not only is industry relying more each year on the power facilities of electric light and power companies but the rapid development of interconnection is giving to industry in general a greater appreciation of the fact that individual establishments cannot make power that will be as reliable as that obtainable from a well interconnected public utility system. With interconnection, smaller cities become attractive to industrial activities. Many of our larger industries, instead of concentrating their manufacturing in one large center, are desegregating their plants and thus securing better working conditions for their employees in localities where there is plenty of room for factories and employees' homes. Interconnection thus has a social value as well as its more generally recognized engineering advantages. It was the interconnection of the private companies that saved the city of Los Angeles from being without service when the St. Francis Dam collapsed.

The completion of the Great Northern project adds another unit to the electrified railroad lines. The huge sums of money involved in this kind of work naturally retard rapid advancement but the advantages of electric trains in some centers and along some lines are overweighing the difficulties involved. The electric light and power companies, also, are persistently pushing farm electrification and thus rendering to rural sections the same advantages that are at the disposal of city dwellers.

The electric light and power industry has been busy and it sees, and the members of this Association particularly see, that it will continue to be busy indefinitely.

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# The Job of the Electrical Industry

P. S. ARKWRIGHT
First Vice-President,
National Electric Light Association
President,
Georgia Power Co., Atlanta

THE electrical industry today faces many problems in selling its service, aside from the matter of simply building power plants, installing and connecting some meters. Among other things, it first must show the prospective customer that electrical service is needed, then it must see that wiring is properly done, and still after that it must accomplish the all-important work of showing the customer how to use his service and of keeping him satisfied that the service is essential to him.

Each of these angles opens a wide field for development. Despite the fact that electricity is used to a far greater extent in the United States than in any country in the world, both for lighting and industrial purposes, a recent survey brought out the rather startling but significant fact that only one-half of the nation's population lives in electrically-lighted dwellings. And this in a day when the half of us using electricity think it impossible for anyone to be without it! This survey also showed that electricity provides only 38 percent of the horse-power requirements of the industries of the United States, in spite of the seemingly large number of industries generating electrical energy in their own plants or obtaining it from central stations.

These figures give some indication of the immense possibilities for further developing the uses of electricity in every field. Rural electrification is just in its infancy, and much work remains to be done in increasing the use of electricity in city residences and in the industrial field. Many of us fail to realize the importance of the small residential customer—we lose sight of him in our anxiety to "land" the big customer.

The proper wiring of homes presents another important problem. During the past several years, the Society for Electrical Development and other similar organizations have conducted campaigns designed to educate the home owner not only to the advantages, but to the absolute necessity of proper wiring. The Red Seal plan, for house wiring, has received the co-operation of building contractors in all parts of the country, but immeasurably greater results could and should be obtained through the whole-hearted co-operation of the central stations.

After having disposed of the question of proper wiring, comes the task of educating the consumer as to the multiple uses to which electricity may be put. He must be shown that the most satisfactory, the most convenient, the most economical way to toast his bread and make his coffee, to clean his house, to operate his factory, and to do the many other things that cause him labor, is the electrical way.

But perhaps the most important work of all is that of keeping the customer sold on his service after he has it. First he must be given a service that warrants all the good things said about it, and a little bit more. Then, by sound logic, it must be proven to him that his electric company is operated for his own personal good, and that to assure an improvement or even a continuance of his service he must help to keep his utility company in a position to give him this service.

Years ago the almost unanimous policy of public utilities was to veil their work with secrecy, to tell the public nothing. That is in direct opposition to the progressive policies of today. Today the customer, through advertisements and other forms of publicity, and through opportunities for personal inspection, is shown "what makes the wheels go round". He is told what the company serving him is doing and what its aims and ambitions are for the future. He is given opportunities to make the company truly his own, through purchase of the company's stock or other securities. The customer must be shown that the company, like himself, is human, operated by human beings; that it is his company, operated for him, and that it constantly is striving to perfect methods by which it may better make his life easier and more enjoyable. He must be shown that, without him, the company could not operate at all, that his interests are intertwined irrevocably with those of his company, and that the company needs him even as he needs the company.

So after all, selling its service presents to the electrical industry many things aside from the construction of power plants and transmission lines. It offers a job that has no end.

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# The Intangible Interconnection Between Utilities

JOHN B. MILLER
Second Vice-President,
National Electric Light Association
Chairman,
Southern California Edison Co.

WHILE the physical interconnection of electric power companies has become a matter of public recognition and discussion in recent years, the public has found out only in the last few years the great benefits both to the corporations and to the public served of the great power reservoirs formed by such interconnections furnishing, as they do, great assurance not only of an ample supply of power but of greater continuity of service. In addition to this, ever since public service corporations came into existance, there has been an intangible interconnection between all corporations furnishing service of some kind to the public. I refer to the fact that whatever of good or evil effects one public service corporation, a similar, if somewhat remote, effect is felt by all the

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other public service corporations. For instance: When Commodore Vanderbilt in his day and generation, being at the head of a great railroad corporation, said to a young reporter who endeavored to get an interview "The public be damned", (and by the way it is claimed, and I have no doubt but that it is true, he never uttered such a phrase but the words were put into his mouth by someone bent on furnishing a sensation) in the minds of the public all the other railroad systems of that time, as well as the Vanderbilt system, were affected by the remark and the public felt that that remark reflected not only the attitude of the Vanderbilt system toward its public but the attitude of every other railroad.

The same inter-relation is true today, not any more so of our industry than any other, but equally so, and every incident affecting the relations of one public service corporation with the public that it serves, has a certain influence upon the public relations of the other public service corporations. One of the most and important and beneficial functions of the National Electric Light Association, important and beneficial not only to the corporations but to the public that it serves, is that among all the other activities of the Association, technical, economical and social, it furnishes a forum and meeting place where the leaders of the industry and, in fact, the representatives of a great part of the whole industry, have the opportunity to get together and discuss not only questions of national policy but local questions in the light of their effect upon the entire industry. For that reason it behooves us to take advantage of this opportunity to do our share of the work of the Association and, above all things, to be constant in our attendance, and in our participation in its meetings, to the end that the intangible interconnection between companies may be made an asset and not a liability; a thing of value to the companies and the public just as is the physical interconnection.

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## The Electrification of America

M. S. SLOAN
Third Vice-President, National Electric Light Association
President, Brooklyn Edison Co.

MR. EDISON expressed recently what I consider to be the ideal of the electric power and light industry when he said that its job would be incomplete so long as there remains for man or woman a single task which electricity could do better. In less than half a century of existence our industry has gone far. From an experiment which was regarded with wonder, and widespread skepticism in 1882, electric central station service has come to be recognized as an essential, vital in our modern conditions of life. It has spread from our largest cities to villages, hamlets and farms. It has lightened the burden of physical labor in homes and work-places of every description. It is hailed as a basic element in our national prosperity and as a potent, beneficent agency of social service. In accomplishing all this, the industry has made itself large and prosperous, as it deserves to be, on its record of things done.

Yet good business sense and obligations arising from the public service aspect of the business make it evident that the industry has no right to any feeling of complacency. Men and women are still doing tasks which electricity could do better. The average use of electricity in the homes of the country is only about a kilowatt-hour a day. There are thousands of mills and factories not yet electrified. Electric power has only made a good beginning of its work on the farms. There is just about enough railroad electrification in the country to prove the benefits which will accrue from a general displacement of steam as motive power.

Such facts are no indictment of the industry, but they are a challenge to it. They are a challenge, to the commercial enterprise of the industry. Our product is electrical service, and our job is to sell it everywhere it can be sold, for as many purposes as it can be used for, and as much of it as can be made to be useful. We know that most homes can use more than a kilowatt-hour a day and the people in them benefit by the use, because we have the evidence of other homes which do use a great deal more than that quantity. We know that many, at least, of the factories and work-places which are not on our lines could profit by use of our service, because others in similar kinds of businesses are doing so. We cannot expect to score 100 percent, but our score, as a business, can and should be made a good deal higher than it now stands.

Our social obligations likewise should impel the industry to advance the electrification of America just as rapidly as the progress of our art and economic conditions will make possible. Our industry is custodian of this great social force, use of which results in toil saved, leisure gained, products manufactured in greater volume at low cost, hence better wages and higher standards of living. These are considerations which we have by no means overlooked in the past, but to which we cannot afford not to give even greater attention in the future. The nearer we come to 100 percent electrification, the better we shall be living up to our social obligations, and the more completely we shall be doing the job entrusted to us with our charters and our franchises.

Our industry has by no means been a laggard, but it has perhaps had things too easy for a period of years. Technically we have made magnificent progress, and we have worked for it—worked hard. If an equal amount of brains and effort had been devoted to the commercial side of our affairs—and after all, we ARE a business, it isn't unreasonable to believe that we should be somewhat nearer the 100 percent score than we now are. We shall have to do so from now on, for it will be impossible to maintain the rate of growth of recent years without greater effort and greater ability in selling our service. The industry

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which on the technical side has done what the central station industry has done in perfecting its processes of production and distribution and lowering its costs cannot fail in marketing its product unless its management is one-eyed. We have been able to reduce costs and reduce rates. It becomes necessary in the present stage of development to devise sales policies, rate schedules and business practices which will enable our business and the public to take fullest advantage of our technical progress.

Our country has, unquestionably, the finest electrical service in the world. It is not the country having the highest average of homes using electricity, or the highest per capita use of electricity. We have won laurels, but we can by no means afford to rest on time.

## Politics, Propaganda and Public Service

W. ALTON JONES
Fourth Vice-President,
National Electric Light Association
First Vice-President, Cities Service Co.

THE quasi-public nature of the light and power business has made the industry the target of petty politicians. From the beginning of the industry, political demagogues—municipal, state and some times national—have picked out the public utility corporation as the object of their attacks. For years soap-box orators from Main Street to Wall Street have preached on the text of "Dangers of Monopoly", "Down With the Power Trust", and other meaningless and vicious themes. Tons of propaganda material have been distributed throughout the country opposing private ownership of public utility companies.

For many years the executives of light and power companies made no attempt to answer the attacks of the political demagogues by the dissemination of factual information about the industry, but were content to go on year by year rendering a greater public service. More recently the light and power companies have realized that they must not only render adequate service at reasonable rates, but they must also gain and hold the confidence of the public they serve, if they are to protect the property of their stockholders from political pillagers.

Generally speaking, the light and power industry today enjoys a good measure of public confidence, but the political demagogue still yaps at the heels of our business and, in spite of the fact that the history of American industry shows that the light and power business has rendered a greater public service than any other business, the political shyster still cries from the soap-box and at times is able to draw a respectable crowd to listen to him. If the palaver of the demagogue falls upon the ears of an informed public, the light and power industry has nothing to fear. If, however, the executives of the light and power companies fail to do their full duty in the employment of every legitimate method of gaining and holding the goodwill and confidence of the public, they are playing into the hands of that group of so-called reformers and false prophets who have for years preached doctrines which strike at the fundamental principle of our American prosperity—private initiative.

## Electricity---the Great Civilizer

E. M. HERR
President, Westinghouse Electric & Mfg. Co.
Member, National Executive Committee, N.E.L.A.

WE hear a great deal about the prevalence of crime, and the difficulty of adequately controlling the criminal, and yet a study of the situation will clearly show that the number of law-abiding people and their influence far transcends that of the lawless and criminally inclined. The revolutionary inventions of our period, made possible by our law-abiding citizens, in which electricity has played so prominent a part, have placed us in a world of unexampled progress and comfort.

The use of electricity for lighting the home and office is widespread. Since its first small beginning, steady progress has been made in the quality of the illuminant furnished until today all other forms of artificial light have practically disappeared and to supply the present demands of our people more than five hundred million incandescent lamps were manufactured last year in the United States alone. The benefits derived by people all over the world from this usage cannot be grasped nor measured, yet I do not think it is exaggeration to say that the incandescent lamp has probably brought more comfort and joy to mankind than any other single thing which I can mention.

Transportation has been revolutionized by the automobile which carries us hundreds of miles in the same time it would take a horse to carry us one-tenth the distance. And yet the greater speed and comfort of the automobile can only be used with safety on streets and highways which are adequately lighted. More than two years ago Superior Street in Cleveland, was brilliantly lighted with 25 000 lumen lamps and since then, says Mr. Dickerson in his paper entitled "Speeding up Traffic Safely", there has not been a single night fatality.

It is said that the night traffic accident record for the entire United States amounts to a total preventable accident loss of about $50 000 000 annually—more than is expended for street lighting each year. This stupendous sum is attributed to traffic accidents alone, and takes no account of night crimes, both of which are almost non-existant in districts where there is adequate street lighting.

Several large cities are now developing comprehensive plans for improved street lighting, the most extensive of these being in St. Louis, where, to carry on this work, financial provision has been made by a bond issue of $8 000 000.

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While better lighting by means of electricity has played no small part in the progress made by civilization during the past half century, there are many other uses to which electricity has been put which have contributed their share also. Were I to take time to show the extent to which our civilization has benefited by the use of electricity in communication, by its many uses as a heating agent, and by its use in providing power for industry, it would require much more space than can be devoted to the subject in this brief editorial.

Farmers constitute the most numerous class of our population, and next to them come the workers in industry. We all know how the workers in industry have benefited by the use of electric power, and how the electric motor now does the work which in other days was only accomplished by exhausting physical effort—thus relieving the workman for the lighter task of controlling and directing the motive machinery and in this way increasing his productive capacity many times.

It is believed by many, on the other hand, that the farmers have received but little benefit from our vast electrical development, and that, because of their location, they can receive but little benefit from it. This is not a fact. To the superficial observer it appears impracticable, if not impossible, to provide the extensive network needed to furnish power to the individual farmer, because of the widely scattered population in the rural districts. A careful study of the situation, instituted by the National Electric Light Association, is being carried on by Committees in more than half the States. Much progress has been made and there is every indication that means will be found whereby the farmer can be served with light and power as easily as is the dweller in the city. The final solution of the problem is closely bound up with that of decentralization of industry.

The use of electric power makes possible the decentralization of industrial activities because power can be brought with ease and economy to the locality where employment conditions are most advantageous, or to the source of supply of the raw material—electric power not being subject to the great limitation of steam or hydraulic power, both of which must be used at the place where produced.

The widespread improvement in the highways throughout the country, and the reduction in cost of the automobile, make it possible for industries to draw their workmen from considerable distances and also permits the workmen to live sufficiently far away from the congested districts so that they may enjoy fresh air and sunshine and have their own gardens, if they desire.

It is significant that, of all the electrical power provided by public utility plants in the United States during 1927, the Department of the Interior reports that slightly less than fifteen percent was used in New York State and nearly ten percent in California; that much of the power used in California is distributed to the rural districts while that used in New York State is more generally consumed in urban industries.

No true picture can be formed of what electricity has done for our people without mentioning Radio—the newest field for its use—a field which has grown by leaps and bounds during the past eight years, until today entertainment and instruction are being broadcast throughout the land, to the dweller on the lonely farm as well as to the dweller within the city.

Thus it will be seen that electricity is closely allied with nearly every line of human endeavor and that, in calling it "the great civilizer", I have given to electricity a title to which it can justly lay claim.

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## The Engineer Has a Sales Objective

C. ERNEST GREENWOOD
Commercial Director,
National Electric Light Association

WERE we to take inventory now of the outstanding accomplishments of the power industry, we would list boldly the service to approximately 18 000 000 homes in urban and rural communities; the acquirement of about 45 percent of the total power used in industry, and reliance of hundreds of thousands of commercial institutions on electric service. And on the financial side, we would point with pride to approximately $9 000 000 000 of investment, and perhaps a million and a half security holders who furnish the capital for building stations, transmission systems and distributing systems to furnish this stupendous service supply.

The construction work called for and the expenditures of these vast sums on service supply have been in the hands of the engineer. Public contact in connection with negotiations for the service, and the sale of the "service" has been under the supervision of commercial men. It is not surprising that viewpoints differ. Engineering "minds" have been assumed a handicap to progressive commercial accomplishment, and the commercial "mind" is assumed to be part of a visionary individual with strange ideas.

Is it not time now for unified thinking in our industry and the acceptance of one fact—the power company must market its product vigorously in competitive fields. Otherwise there is no need of the manufacturing staff to meet a growing demand. The business of the manufacturer of electrical equipment of all kinds depends on the diversified sales of the power company, and "normal growth" in sales is not sufficient in these days of vast capital investment in plant and equipment, to content us as the only demand. The sales market must be broadened. The "strange ideas" of the commercial men can solve the problem, and behind the service sold there will be keen engineering minds to keep the pace of supply ahead of demand.

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Thus unified thought and action of engineering and commercial men is essential. They are going to understand one another better. The Engineering Department at the Headquarters of our Association has already shown its helpfulness to the Commercial Department in the field of investigation, and plans are laid for further co-operative development of a background for commercial action. A reflection of such unified action is needed throughout the country. Surely the men engaged in both these fields of endeavor have a common objective, SELLING and SERVICE. The terms are synonymous, and further achievements of the industry will depend on the co-operative effort by engineer and sales executive to gain that objective.

## We Must Keep Up With the Procession

MAJOR H. S. BENNION
Director of Engineering,
National Electric Light Association

OUR ever-growing population and the increasing complexity of our civilization continually give rise to new and enlarged problems. As fast as these problems are recognized, there follow efforts on the part of all concerned to take advantage of the new interest or to deal with the new problem. New organizations form or old ones are realigned, each having particular aims which it strives to promote. To the man on the staff at N.E.L.A. Headquarters dealing with codes and standards questions, this is emphasized by the fact that our Association cooperates with over 300 other organizations in standardization work and has from one to twelve representatives on about 150 standardization bodies.

Of the industrial problems arising from modern development, standardization, codification and simplification are among the most important. Few are more difficult of accomplishment; none contain larger benefits. This work calls for the concerted action of a large number of experts dealing often with complicated and tedious details. It demands a high degree of co-operative effort on the part of many large bodies—technical, commercial and governmental; it involves the producer, distributor and consumer. Enormous savings have been and are still to be attained from standardization and simplification. The public interest rightfully demands that full advantage of its possibilities shall be taken. On the other hand, the fixing of rigid standards too soon, especially in an industry which is new and undergoing rapid and scientific development, may curb and stifle improvement.

It will be readily appreciated that the handling of these standardization problems presents a very difficult task, calling for nice judgment in weighing the economic and commercial factors, in balancing immediate advantages against future probabilities and in finding the practical solution as opposed to the ideal. In the good old days, when amounts involved were much smaller, developments were fewer and there was more elbow room, and when interests were not so closely interwoven, the working out of codes and standards was largely accomplished by the offhand judgment and by the verbal recollections of experienced men. This procedure is no longer adequate. The interests at stake are so large and the adoption entails such important consequences, that the public interest has a right to require more precise and scientific methods. Definite records and carefully compiled facts must be presented in support of any proposed standard or code provision before its adoption can be justified.

The collection of necessary facts from an industry covering the whole country is a burdensome task involving considerable expenditures of money and effort. There is sometimes reluctance on the part of companies to share in this heavy burden. It arises largely from failure to recognize the extreme value and importance of participation in this work. And naturally the question has arisen as to the necessity for starting elaborate methods of procedure which the industry has gotten along without heretofore. The answer is that the growth of industries to large proportions, creating more and more points of interrelation and more fields of interdependence, carries with it a need for increased attention to their dealings with all agencies involved. The responsibility for participating in work for the public interest and the general good cannot be neglected. All must keep up with the procession if we are to make real progress.

## The Engineering National Section

E. C. STONE
Chairman, Engineering National Section, N.E.L.A.
Manager, System Development, Duquesne Light Co.,
Pittsburgh

THE committees of the Engineering National Section have enjoyed another successful year. Analysis of the personnel participating in the work work shows that practically all of the major power systems in the United States are represented on them by engineers in authority in their respective organizations. By the high quality of their personnel and the effective work done, the Engineering Committees have won for themselves an outstanding position in the industry. Unquestionably the motive force back of the success of this committee work is the opportunity afforded for each engineer to meet other representative engineers from all over the country for personal contact and exchange of ideas and experiences on problems of mutual interest. The value of this contact can hardly be over-estimated, especially where the growth of business and engineering development are as rapid as they are in the power industry.

The work of the committees is expressed in results along two major lines:—

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Educationally, as manifested in the discussions and exchange of experiences which take place in the committee meetings and in the serial reports on important engineering subjects that are issued from time to time.

In engineering policies, giving authoritative expression of sane industrial practices, which are set up as needed on matters pertaining to codes and standards, joint construction with other utilities and other subjects in which the industry has engineering contact with other interests.

Closely associated with the National Engineering Committees are the corresponding committees of the Engineering Sections of the twelve Geographic Divisions. These Divisional Committees have been better organized and more active than ever before during the past year and, with the National Committees, make up a comprehensive group representative of the entire industry. This larger group is, in the engineering field, effectively fulfilling one of the major purposes of the N.E.L.A. which past President Ballard has defined to be "to perfect ourselves in detail through this Association to ensure that each member-company is kept up to the highest standards of our best."

The specific accomplishments of the Committees of the Engineering National Section are outlined in the editorials by the chairmen of the specific committees. The work in general is directed towards certain objectives which have been defined by the executive committee of the section as follows:—

More system capacity per dollar of investment.

Definite advance planning of system development, and co-ordination of adjacent systems.

Comprehensive research in fundamental engineering problems of the industry, co-ordinated through the committees.

Constructive co-operation in the national movement for standardization.

Recruiting and training of adequate personnel for the industry.

The power industry will undoubtedly spend more money both for operations and for additions to plant during the next ten years than it has spent in any previous like period of time. In capital improvements alone it is quite reasonable to suppose that as much as ten billion dollars will be spent. Our engineers will be responsible for specifying how these huge sums are to be expended. Furthermore, the exacting demands for the highest possible grade of service and the economic pressure to get the greatest possible value out of every dollar spent, as well as the more intricate engineering problems coming from the enormous amounts of energy to be handled and the vast networks of transmission and distribution required to handle it, will make the engineering problems of the future more complex than those of the past, so that both the magnitude and intricacies of the situation will make it necessary that particular attention be given to the recruiting and training of an adequate engineering personnel to handle them.

# Power Plant Development as Seen by the Prime Movers Committee

EDWIN B. RICKETTS
Chairman, Prime Movers Committee, N.E.L.A.
Research Engineer, The New York Edison Co.

THE past year has not been characterized by any particularly striking developments in the more important characteristics of power plant apparatus, but has rather been a period devoted to what our military friends would call the consolidation of our positions made necessary by recent rapid advances. The accomplishments along this line are well reflected in the reports of the various Sub-committees of the Prime Movers Committee now in course of publication. While it is obviously impossible in a short editorial to review the reports of this Committee adequately, it may be advantageous to call attention to a few of their more important features.

The increasing use of water-cooled furnace walls has emphasized the necessity of providing ample water circulation to these surfaces on account of their high rate of heat absorption and consequent high velocity of circulation.

The Condenser Report notes the increasing use of single-pass condensers and the installation of a condenser having tubes expanded in both ends, at the Gould Street Station, Baltimore.

The Higher Steam Pressure Report presented economy data on ten plants operating at pressures ranging from 310 to 1200 lbs. In connection with the operation of 1200 lb. plants, the necessity of reducing scale formation to an absolute minimum by careful feed water treatment is emphasized. The present status of research in the properties of metals at high temperature is reviewed.

The Sub-committee on Power Station Betterment, which this year was given the problem of recommending methods for obtaining the best operating efficiency from existing equipment in old plants, presents four carefully worked out methods for following plant performance and checking plant efficiency.

In the Pulverized Fuel Report, the operating results of a number of representative pulverized-fuel plants for the year 1927 are given in detail, the increased tendency toward the unit system of pulverization is noted and the year's progress in the development of mixing burners, dryers and other equipment is discussed.

The Stokers and Furnace Sub-committee reports that the installation of automatic combustion control is giving results which indicate its utility and value. Stoker capacities are being increased to meet the demand for higher heat liberation per sq. ft. The use of water-cooled furnace walls is decreasing stoker maintenance in spite of the use of preheated air up to 500 degrees F.

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There is a continued interest in the use of coal distillation in connection with power plants, much experimental work is in progress and several commercial plants have recently been placed in successful operation. It is, however, too early to draw definite conclusions as to their economic value.

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# Should Our Water Power Resources Be Developed?

PAUL A. SCHOELLKOPF
Chairman, Water Power Development Committee, N.E.L.A.
President, The Niagara Falls Power Co.

THE total water power resources in the United States available fifty percent of the time is estimated to be 55 000 000 horse power. The combined capacity of all power units installed in central stations, electric railroads, industries, mines and quarries in the United States on January 1, 1928, was about 60 000 000 horse-power with several millions more in locomotives used in railway transportation. It is evident, therefore, that the total water power resources, even if all could be developed and brought to market at once, would not meet present power demands. Much of the undeveloped portion of the above mentioned 55 000 000 horse-power is not economically feasible of present development. However, that which is feasible should be developed as soon as practicable because, until developed, it produces nothing, and when developed it will continue to produce indefinitely, not being depleted by use as are most other resources.

For the past twenty years, the importance and value of our water power resources have been so extravagantly urged upon the public by conservation enthusiasts, government operation advocates, and others, that no sane and reasonable policy of dealing with the development of water power has been able to exist for long. In June 1920, after twelve years' discussion in Congress, the Federal Water Power Act was made a law and established policies for dealing with water powers under federal jurisdiction. While not completely satisfactory to anybody, the Act was workable and great activity in water power development followed its passage. Under the Act, at the close of 1927, 128 projects with a proposed ultimate installation of 4 610 000 horse power were completed or under construction.

Eight years of operation has demonstrated that, whatever else may be said of the Act, it certainly is adequate to protect public interests under all conditions. In spite of this fact it has been subject to attacks which have increased each year, until now it practically has become inoperative with respect to many of the largest and most feasible power prospects under federal authority, such as the Tennessee, the Colorado and the St. Lawrence. In fact, in the past two years, water power appears to have become, more than ever before, a political football, not alone in federal politics but also in state and municipal politics. The result of the political discussions has been to establish, in the public mind, such an exaggerated idea of its value that one desiring to develop water power at this time is confronted, not only with great difficulty and expense in securing the necessary property and water rights, but with long and costly delays in obtaining governmental authority. A marked falling off in new water power development has resulted. From 1923 to 1925, inclusive, the annual increase in installed water power machinery ran from 10 to 14 percent, whereas in 1926 and 1927 it was less than five percent.

Remarkable reductions in steam power costs in the past three or four years have contributed to the falling off in new water power development by making economically unattractive many projects that looked promising in the period 1920 to 1924. Still further reductions in steam costs may be looked for, but notwithstanding this competition, there are still many water powers economically susceptible of development, and the earlier they are developed the more the public will profit from them. Early development cannot be accomplished unless definite policies, both federal and state, can be adopted and adhered to.

While the power industry is a complicated one, and a great deal of misinformation has been published about it, any fair-minded person studying the subject can hardly fail to arrive at the following conclusions:—

1—No industry, in the United States, has a better record than the power industry for adequate service rendered at reasonable cost.

2—This country already has adequate laws and agencies in the Federal establishment as well as in most of the State establishments to fully protect public interests in water power developments.

3—The greatest benefits from water power resources can be secured for the public only by developing them as part of the present well established systems. Very few water powers are worth much when developed and operated as isolated plants.

The opposition to the Federal Water Power Act appears to be led by the advocates of government operation. It is a curious circumstance that in this country, which owes its phenomenal prosperity to the freedom given private initiative and to the restrictions on government participation in business, it is possible, under the guise of flood control or irrigation or some other quasi-governmental function, to get consideration for government construction and operation of projects which are essentially power projects and involve putting the government directly and heavily into the power business. The advocates of projects of this kind find the regulatory provisions of the Federal Water Power Act embarrassing and

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have resorted to all manner of expedients to avoid coming under the Act. It is inconceivable that a small, but noisy, minority can succeed in converting this country to the European system of government operation, but they certainly have been, and are, successful in delaying water power development, and the public is paying for the delay.

## Electric Industry Faces the Task of Commercial Development

JOHN J. O'BRIEN
President, H. M. Byllesby & Company
President, Standard Gas & Electric Co.

THE future growth and development of the electric power and light companies, in my opinion, depends upon how well they develop the uses of electric service in the home and industry and how they extend its benefits to new fields. In the recent years of prosperity it has been a comparatively easy matter to add revenue-producing load. In many cases, in fact the utilities have been accused of "skimming the cream" in taking on new business. This, however, was only a natural development. With industry making tremendous demands for service, and home building breaking all records, it was all the utilities could do to install the required generating capacity and extend lines to serve new customers. This period of expansion necessitated large capital investments, which in many cases have not yet been fully utilized, resulting in poor load factors. To improve these load factors, to make every dollar invested in plant and transmission lines work as nearly as possible twenty-four hours a day, year in and year out, is the job the industry faces today,

The market for electrical devices in the home has scarcely been opened. Concerted efforts on the part of all branches of the industry will bring about the rehabilitation of inadequate domestic wiring which now limits the customer to the use of few lights and fewer labor-saving appliances. In industry, wider uses for electricity as motive power and as heat will extend the market for this class of service. We are just touching the edge of the enormous rural market, but this development will necessarily be slow, and must be preceded by sound educational policies before we can presume to go after it in earnest.

The market for electricity is here, however, waiting to be developed, and as the industry has successfully solved problems of engineering, finance and management in the past, so will the problems of new business development be conquered. As a whole, the utilities of the nation are in a position to develop the markets for their service without unduly large capital investment. They are well built, well financed and well managed. The public recognizes the fact that they furnish an essential service, and the public authorities, in general, are co-operating rather than interfering with their development.

Commercial development, then, is the first order of business on the program of the electric industry. The rewards will be the more efficient utilization of our existing investments and better and more useful service to our customers.

## Work of the Underground Systems Committee

J. W. SYLVESTER
Chairman, Underground Systems Committee, N.E.L.A.
Engineer Trans. & Dist., Philadelphia Electric Co.

JUDGED from the standpoint of attendance and interest taken in the meetings, those of the Underground Systems Committee for the current administrative year have been most successful. The average attendance at the three meetings, at Chicago, Newark and Louisville has been ninety, indicating an increasingly greater interest in the subject of underground design and construction. This has been brought about, no doubt, by the greater attention being given to this subject by the smaller companies which formerly found no use for it, but also because of the continuing of the practice established by the present chairman's immediate predecessor of preparing a detailed program outlining clearly the subjects to be presented and discussed which included not only the prepared reports by certain of the subcommittees but other special subjects which had been prepared in advance by representatives of the member companies. These programs were very closely adhered to and considerable discussion was invited by the advance distribution of the reports.

The Underground Systems Committee consists of the following subcommittees:—

Cable Installation
Cable Sheath Damage and Protection
Conduit and Manhole Temperatures
Impregnated Paper Insulated Cable Research
Inspection and Testing of Cables
Alternating-Current Networks
Conduit and Manhole Construction
Cable Joint Design and Construction
Cable Operation
Underground Systems Reference Book

Substantial progress is being made in the preparation of the Underground Sytems Reference Book which will be of great value to the industry, particularly among the younger engineers and smaller companies where such a reference book is most needed. A staff of editors has been selected and an effort is being made to complete the manuscript by the end of the present calendar year.

A symposium on the subject of cable research under the auspices of the Impregnated Paper Insulated Cable Research Subcommittee held at the Louisville Meeting gave the committee members a very clear idea of the extent of research work being conducted along these lines, not only at Johns Hopkins, Harvard and Massachusetts Institute of Technology, under the guidance of the N.E.L.A., but also at the University of

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Illinois, at the Electrical Testing Laboratories, by the National Research Council, the cable manufacturers, the Association of Edison Illuminating Companies and one of the public utilities. As the members of the N.E.L.A. Research Subcommittee are also members of the similar committees in other organizations, an excellent opportunity is afforded them to co-ordinate the research program so as to avoid duplication of effort.

The reports of the Subcommittees on "Inspection and Testing of Cables" and "Cable Operation" indicate that the manufacturer is producing a better cable according to routine factory tests and that fewer faults per 100 miles of cable are occurring in actual operation. Still greater improvement in cable operation lies well within the reach of the user as faults due to improper installation, poor workmanship, mechanical injury, etc., are five times as frequent as those due to internal or electrical failures.

In order to derive greater benefit from the reports of these two subcommittees, another committee has been appointed to study these two reports in detail and to report back to the main committee with recommendations. A very complete resumé of the practices of various companies operating or planning alternating-current networks was presented at the Newark Meeting.

The Subcommittee on "Conduit and Manhole Construction" presented a comprehensive report on up-to-date and unusual practies in this field, among which might be mentioned duct sections 1000 feet long, thereby eliminating unnecessary manholes and splices therein; the tendency toward larger ducts permitting the use of the three, large single-conductor cables in one duct toward which there is a trend; the construction of a monolithic concrete cableway on a rocky surface over a private right-of-way; buried cable installations; concrete manhole construction with a rising steel form; pre-cast concrete manholes, service boxes, etc.

The company making the duct sections 1000 feet long found that it was possible to install cable therein with a maximum pulling stress of less than 7000 pounds. This company has also demonstrated the economy of installing three single-conductor 600 000 c.m. cables in one 4 inch duct in place of two three-conductor 350 000 c.m. cables in 3½ inch ducts. Further, it is also considering the installation of three single conductor 1 000 000 c.m. cables to operate at 11 000 volts in a 5 inch duct. Comparative analysis of the cost of such installation as compared with three conductor 350 000 c.m. cable in separate ducts, both designed to transmit the same load, indicates a saving of 59 percent over the latter in conduit system alone. A further saving of 25 percent in the cost of cable is secured by this somewhat radical change. This report demonstrated quite clearly that the members are alive to the advantages and economies to be secured where unusual conditions exist or where standard practices can be improved.

During the past year two installations of cable operating at 132 000 volts, one in Chicago and one in New York, have been placed in service and up to May 1st have been operating under practical loading conditions without failures to cable or joints.

An interesting demonstration was given to the members who attended the Chicago Meeting of the effects of poor workmanship on splicing material, insulating compound and other materials used in the making of cable joints. Similar demonstrations have been made before the cable splicers of a number of companies and improvement in the work produced, indicated by fewer failures in cable joints made after such demonstrations, have been reported by these companies.

As indicated above, in the growing attendance at each committee meeting, in the pertinent discussions that follow the presentation of each report, in the broadened activities of the Geographic Divisions as reported by their respective representatives and as shown by the very complete reports presented at their annual conventions, a very much wider interest is being taken from year to year in underground construction and practices, and ever-varying problems are being presented to practical engineers for solution.

## Economic and Governmental Regulation Inseparably Mixed

EDWIN D. DREYFUS
Engineer, Pittsburgh, Pa.

THE utility atmosphere is now and then surcharged with pressure for investigations of various sort, or else restrictive regulation looms up on the horizon in some new form. These conditions may temporarily produce a dull cast overhead with attendant uncertainty. Like inclement weather, they eventually blow over, leaving either little or much damage as the case may be, but with the distinction that they are usually the result of artificial rather than natural causes. Nothing takes its toll as unfailingly as economic forces when business operations run contrary thereto. The casualty list grows when industries override economic limits or are unduly hampered in developing along the broadest and most effective lines. Therefore, regulation should provide both caution and stimulation to ensure beneficial growth of the industry.

Our government has served a very useful purpose in reducing destructive competition between like public utilities, thereby eliminating one element of economic regulation. In turn, the public is entitled to protection against the apparent monopoly created, so that abuses are prevented. But, on the other hand, the business is by no means entirely freed from competitive forces, as the people served may yet limit their patronage or satisfy their wants through other channels. It would appear that in case of governmental regulation, outer safeguards are sufficiently secured through a complete system of public rate and tariff files, prescribed systems of accounting, approval of new financing and con-

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solidations, regulation of service standards, and filing annual reports. Therefore, the internal affairs or inner workings of the business may properly be left to the management so long as the overall results do not exceed reasonable bounds and the communities served give evidence of a progressive policy on the part of their local utility when compared with other sections similarly situated. Unduly rigid regulation, demanding minute details intended for an academic supervision may unsuspectingly dwarf or improperly hold in check the development of an industry on account of the grave danger that theoretical reckoning may not be consonant with the controlling factors of the business. Such has happened in the past with a distinct loss to the public affected.

No arbitrary barrier may be interposed that will deflect that inexorable law of supply and demand. With a sincere purpose of promoting the general welfare, these problems should be approached by the legislative and regulatory bodies with a broad perspective and the industry itself must, and undoubtedly will, establish by its conduct and the results it produces the necessary evidence of good faith.

It is the unfortunate exceptions held up as bad examples that create an undesirable odium, but an entire community or industry should not be excessively regulated on account of a few culprits. Offenders should be brought to time by specific action, rather than by restricting the latitude necessary for the industry to meet the play of all economic forces.

## Heater Cord Standards

FRANK THORNTON, Jr.
Chairman, Joint Committee, N.E.L.A. and N.E.M.A.,
Manger of Engineering, Merchandising Dept.,
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MANY a well designed electric iron or percolator has been set aside as useless when there was really nothing wrong but a broken cord. This gives the housekeeper a poor impression of the reliability of electrical equipment, which causes her to hesitate before purchasing any more; and is apt to be reflected in the attitude of her husband when he is considering equipment for office or factory use. Two things are necessary to overcome this fairly prevalent frame of mind. One is to educate the public to understand that no cord will stand continual pulling or jerking—it must be handled carefully and if used much it must occasionally be replaced. The second and most important is to use better cords, especially for electric irons, where the service is exceptionally severe, and abuse all too common.

Many of the cords now on the market will stand hard service. Others will not. To eliminate the latter, and to assist in improving the former has been the function of a joint committee consisting of representatives of the Wiring Committee, N. E. L. A., and Wire and Cable Section, and Heating Appliance Section, N. E. M. A.

The first important problem of this Committee was to find a method of testing cord which would be reliable enough to indicate the relative durability of various samples; and second, to determine some minimum standard under this test method. Once such a yardstick were provided, it was felt that the manufacturers of appliances could set some standard to which the cord makers could adhere, as they would have a uniform means of testing their product.

The actual development of the testing method and the testing machine was entrusted to the Underwriter's Laboratories, and the work was done under the direction of Mr. C. J. Krieger. The test finally evolved is a repetition of twisting, pulling and jerking the cord, is consistent in results and gives a very close indication of relative life in actual service.*

The work of developing the test method was long and tedious, because it involved careful checking of the laboratory results by experience in actual use on a larger number of samples. This phase of the work was guided by Mr. R. S. Hale of the Edison Electric Illuminating Company of Boston with the co-operation of a large number of electric service companies. It is because of the careful check between service performance and laboratory results that the committee finally concluded that the laboratory test method was sufficiently reliable to permit of its use as a standard. It has, therefore, been adopted as a part of the "Underwriters' Laboratories' Standard for Heater Cord". Purchasers of heater cord who specify this standard, now may know that their cord is not inferior to the minimum requirement. It is possible, of course, to specify test requirements higher than this minimum, and many manufacturers of appliances have already taken such steps for certain of their products.

## Something New in Standards

W. S. RUGG
Vice-president,
Westinghouse Electric & Mfg. Co.

LONG ago it was recognized that standards are necessary, and desirable. Before the adoption of standards, the design of electrical apparatus, in general, was chaotic. The simplification of design, manufacture and distribution processes which resulted when agreement was finally reached on even the simpler forms of standardization was astonishing.

These advantages of standardization have been so evident that its province has been continually extended to include, one by one, such things as speed, voltage, frequency, insulation, markings, terms and, lately, dimensions. In fact, nearly all of the individual qualities of equipment have been included. It is quite in order that there be added to this impres-

*A detailed description of this test is given in a report recently published, copies of which are available at the headquarters of the N. E. L. A., N. E. M. A. and Underwriters Laboratories.

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sive list—standards of performance. The proposal has been made and is being considered that a minimum standard be established for all the important performance characteristics of each of the various electrical equipments. Thus an induction motor, for example, whose efficiencies, power-factors, torques, speed regulation, etc., did not meet certain minimum requirements would not be considered standard. The minimum standard would, of course, be the highest standard reduced to what is practical and economic for all.

Clearly, the immediate object of such a code is balanced design. A minimum standard for the performance of any piece of electrical apparatus would require that all essential characteristics be such as to provide for a generally satisfactory performance. Unbalanced design always results from special emphasis upon some particular characteristic. Both the producer and user gain when machinery and apparatus designs are properly balanced, and when no one characteristic is over-emphasized to the detriment of some other.

When a performance standard is made by the manufacturer, and is accepted by the users, low cost production and distribution can be achieved. In periods of depression, manufacturers can build up stock with the positive assurance it will be salable when business improves. The user is assured of an article at all times of standard quality. Experience shows that defectives are much more frequent in articles of special characteristics, or those made in relatively small quantities, than in standards made in large quantities. Standard quality and large quantity production is not undertaken until the manufacturer is quite sure that the design, material and process are as perfect as possible. Thus, though the immediate object is balanced design, the ultimate object is an economic one—a gain for all concerned.

A minimum performance standard would provide a bench mark for the entire industry. At any given time this mark would represent the best judgment of all concerned, and would form the most satisfactory commercial decision possible at the time. Also, it would provide a point of departure for improvement when and if new materials, new developments in design or new requirements make it desirable to change the standard. This bench mark would not be fixed—not the same today and tomorrow and forever—but dynamic, to be raised as the average ability of the industry makes it possible.

The suggestion of the adoption of minimum standards is simply another step in a change which has been taking place in industry for many years, tending towards greater efficiency in production and more satisfactory apparatus for the user's purpose. It is simply another step in standardization which goes hand in hand with efficiency.

# The Development of Public Utility Prime Movers

A. D. HUNT
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HOUSEHOLDERS who use electric current, expect unfailing response to the turning of a lighting switch, but comparatively few know of, or appreciate, the amount of scientific research and patient experimentation that has been carried on over many years to make possible the reliable electric service found today even in the small communities.

Among the vital factors in the attainment of the present-day standard of service and low current cost has been the development of the central station prime mover—the large steam turbine and the electric generator which it drives. Progress in the art of turbine and generator design has been phenomenally rapid and no decrease in its rate of advance is apparent. Hence, it is interesting to look ahead and to consider the expectation of future developments, which today's rate of progress justifies.

In 1900, the company with which the writer is connected placed in service a 2000 kw turbine-generator unit. This event was heralded by engineers as an outstanding achievement. The maximum blade speed in that machine was about 400 feet per second. The maximum blade speed of present-day large turbines approximates the speed of sound or nearly three times that of the turbines of twenty-seven years ago.

The normal steam pressure of central station practice today is about 400 lbs. with a few plants at 600 lbs. The usual steam temperature does not exceed 750 degree *F* total temperature. For such conditions single cylinder turbines may now be considered standard and are to be had in capacities up to 85 000 kw. They are commonly arranged for extraction in four stages for feed water heating. In this class of units 100 000 kw at 1800 r.p.m. seems not impossible.

For larger capacities the cross-compound principle has been applied up to 165 000 kw in two cylinders and 208 000 kw in three cylinders. It now appears practicable to build two cylinder turbines of 200 000 kw and three cylinder units of as high as 300 000 kw capacity.

Steam pressures as well as capacities are being increased. Nine hundred pound, twelve hundred pound and sixteen hundred pound turbines have been built in recent years. Units of standard construction are at present available for these pressures and, where obtainable economies justify the cost, turbines may be built for pressures higher than these.

With the increasing knowledge of materials and their properties at higher temperatures, the limits of such temperatures in practice may be extended to 800, 850 and possibly 900 degrees total temperature within the next few years.

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# The Business of Designing Electrical Machinery

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Chairman, Electrical Machinery Committee,
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**"An engineer is a scientific business man." This definition which so admirably serves the purpose of the present article, was originated by C. F. Hirshfeld of the Detroit Edison Company, and was referred to by E. C. Stone of the Duquesne Light Company in a recent article in the N. E. L. A. Bulletin. At a dinner in New York City in February of this year given in honor of Herbert Hoover by the American Institute of Mining and Metallurgical Engineers, Mr. Hoover defined the engineer as "a technically trained business administrator". This expresses much the same thought, a little differently.**

THE engineer's work is based on science in its dealings with material things, but it must also be directed by the same principles of economics and trade that guide the successful business man, if the engineer's science is to be transformed into engineering. A machine, a bridge or any engineering work, must not only function successfully but, if it be good engineering, it must also meet the test of economic value; it must result in a profit, either in dollars or, in the more general case, in a useful output greater than the effort required to produce it. An engineer then need make no apology if he writes on this subject of designing and building electrical machinery, from a business angle.

There is a popular impression that the electrical industry is a lusty infant that, year after year, increases greatly in size, strength and general activity. This picture is correct in a measure for the industry as a whole, but it is not true if our attention is confined to the business of manufacturing electrical machinery. In this branch of the industry the average annual growth during recent years has been so small that it is masked by the ordinary yearly fluctuations in volume of business caused by changes in general conditions. It may not be generally known that the total volume of business in the United States in steam turbine-generator units, for example, was larger in 1923 than in any later year. The total kw of hydraulic turbine generator units installed each year is decreasing in general trend rather than increasing. The decreasing first cost and increasing economy of steam plants as compared with the increasing cost of hydraulic works, stations and transmission lines, as available sites for hydraulic stations become less desirable economically, is one reason. Another reason—and one that applies to all stations, steam and hydraulic—is the interconnection of existing stations and systems. At the 1928 Winter Convention of the A.I.E.E. it was pointed out that interconnection reduces the need for additional generating equipment in two ways:— The average load factor of the interconnected system is increased, i.e. an increased total integrated load can be handled by the same or less installed equipment; and spare equipment in the several parts of the interconnected system need not be duplicated. Therefore, as long as interconnection is growing, the rate of increase in new generating equipment will be reduced.

It may be of interest to point out an analogous situation in another industry. The more efficient use of generating equipment by means of the interconenction of major systems has its counterpart in the better utilization of railway rolling stock by American railroads.[1] The number of new freight cars ordered in the United States and Canada decreased from 180 900 in 1922 to 145 600 in 1924, and to 68 500 in 1926. As is well known, American railroads handled the largest traffic in their history in 1926. In past periods of maximum traffic, it has been customary for the roads to make maximum purchases of new equipment.

This startling decrease in volume of new car construction has been made possible largely by reason of a program of improving car utilization, started in 1923 by the Car Service Division of the American Railway Association. This activity has resulted in pooling the freight car equipment of the country, moving empty cars to the points where they are needed and utilizing the available supply more effectively. It is obvious that this is a close parallel in cause and effect to the interconnection of public service electric systems. And in both cases the more effective use of existing equipment has reduced purchases of new equipment. However desirable this result may be from the standpoint of the country at large, it has had serious effects on the volume and profits of the interested manufacturers. But, fortunately for us who are in the electrical industry, the electrical manufacturers, with their wide diversification of product, have not suffered so severely from this cause as have the companies manufacturing railway rolling stock exclusively.

[1] This information is from an article by Charles W. Foss in the *Annalist* of Nov. 11, 1927.

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This picture of the electrical machinery business is not, however, all shadow. There are many fields in which the use of large electrical machinery is increasing—in propelling machinery for ships and in a wide variety of industrial applications—to mention only two important fields in which growth is notable. But, on the whole, the electrical manufacturers cannot look forward to any large annual increase in volume of heavy machinery business.

A SUBSTANTIALLY stationary volume of business, then, is the first major fact in the business situation that engineers must consider. The second fact of importance is that there has existed for the past seven years a considerable manufacturing capacity in excess of the country's requirements and of export trade. It is hardly necessary to stress the point that reduced demand for goods, accompanied by over supply of manufacturing facilities—amounting to a potential over supply of goods—has resulted in a falling price level that has been particularly in evidence during the past two or three years.

This condition is not peculiar to the machinery branch of the electrical industry. It is, in fact, a condition most industries have had to contend against during the past few years resulting in smaller average profits in spite of larger volumes, considering industry generally. This situation is well summed up by Mr. Leonard P. Ayres[2], vice-president, Cleveland Trust Company, in a recent article:—

"We are now in the sixth year of a period of prosperity that is developing a kind of business competition never experienced in this country. It is a long-distance race in which the short-winded contestants are being dropped out one by one. Manufacturers and merchants are doing a large volume of business; but they emphatically testify that margins of profit are becoming very narrow. Their testimony is supported by records of business failures which are steadily rising, and which threaten to go up in this year to peaks never before exceeded even in times of general depression.

"This condition is without precedent. In former decades, periods of prosperity were times when everybody had work, and everybody made more money. Now, conditions of employment are good, but a great many business men find it extremely difficult to make any profits. The explanation appears to be:—during previous periods of prosperity the wholesale prices of commodities rose, while during the past two years they have been falling.

"The advance of prices in former prosperous periods meant that the demand for goods was currently a little greater than the available supply. Hence the producers fixed the prices, and the buyers competed for the commodities. Even the less efficient producers were able to make money, and the more daring ones often profited largely by commodity speculation.

"But this period of prosperity is different. The restriction of immigration has compelled manufacturers to install labor-saving machinery, and to make their organizations more efficient. The result is that the factory output of goods per man per day has recently increased so rapidly that we now have a period of sustained trade during which the supply of goods is currently a little greater than the demand, and prices keep falling instead of advancing. Buyers dictate terms, and producers compete for markets."

In January of this year one of the national business and investment statistical organizations published this summary of the situation:[3]

"The comparatively steady decline in industrial commodities since 1923 has been the direct result of enhanced competition in all lines. Manufacturing methods have improved, production efficiency has reached new high levels, and production capacity has increased to a degree somewhat outstripping the rise in actual consuming power. To maintain sales volume under the intensely competitive conditions which these trends created, individual producers had been forced to reduce prices to a degree which cut sharply into profit margins."

A third important business fact, bearing on the present situation, that engineers and others sometimes fail to recognize is that, assuming free competition, the manufacturing costs of an individual manufacturer do not determine selling prices; on the contrary, selling prices are determined by the collective market, and selling prices ultimately determine costs. The individual manufacturer must meet the market and, sooner or later, adjust his costs to afford a profit at the market, or go out of business either from lack of sales or lack of profits.

These, then, are the business facts and conditions that designing and manufacturing engineers have been facing during most of the past decade. Engineers, perhaps more than any other group, are led by training and experience to search for facts, accept them, and modify their plans and methods, as may be necessary, to meet conditions as they exist. A man may be influenced by skillful argument, but a faulty machine cannot be made to mend its ways by such treatment. In such engineering situations nothing counts but the facts and engineers cannot be timid in the face of facts. What, then, are designing and manufacturing engineers doing to meet this economic challenge of a low market price level?

## ORGANIZATION

IN the earlier days of the industry the principal problem of the engineer was to produce a design that would work; anything that would function successfully could be sold at a profit. Manufacturing cost was a secondary consideration. During this phase, when the important question was: "Will it work?"—it was not essential that the designer know much about the details of manufacturing practice. Because of this situation, and also because of the apparent "mystery" that enshrouded the work of the electrical designer in the eyes of the practically trained man, there grew up in the larger electrical manufacturing companies an engineering organization rather isolated from the manufacturing organization and, in some cases, even separated from the mechanical engineer's part of the common problem. Because of the major importance of the scientific basis and method in electrical designing, because of its newness and because of the relatively simple manufacturing technique then sufficient, this general type of organization was natural, and successful, in spite of its isolation.

But these earlier conditions no longer exist. For a decade at least the machinery designer's major

[2] *Review of Reviews*, for October, 1927.
[3] Standard Statistics Company, January, 1928.

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problem has been economic rather than scientific; the business man's role and the manufacturing engineer's role have been growing more and more important. During this nearby period the major problem of the designing engineer in the machinery field has been to produce designs of well-established types that will compete with other designs on the market in performance and cost. Through advances in engineering training and technique there is now little question as to ability to perform; the most pressing question the engineer must answer is: "What will it cost to build?" The design engineer in the scientific engineering department can no longer answer this question unaided. It can only be answered satisfactorily when the design function and the manufacturing function are brought as closely together as possible and, for best results, under unified direction and control.

The first answer to this pressing condition of vanishing profits has been better organization—a broader conception of the design engineer's field and, particularly, the extension of this field into the factory.

### DESIGNING FOR SIMPLIFIED PRODUCTION

From a production or manufacturing standpoint there are three classes of machinery:—

*a*—The completely special, custom-built machine,
*b*—The completely standard machine, built for stock in advance of orders and,
*c*—An intermediate class which is neither completely special nor completely standard.

In the first division are those machines that are so special in size, speed, mechanical construction or performance requirements that they can only be designed after the contract is signed, and must be built "by hand" largely without special equipment or tools. The designing and building processes may be compared with the business of making shoes for club-footed men, or clothing for Tom Thumbs. It is a custom business with a built-to-order product characterized by relatively simple organization, old-fashioned jobbing shop methods and with the accompanying high costs, as compared with the cost of a standard product.

In the second division lie the other familiar classes of smaller machines, mainly motors, which are standardized as to ratings, speeds and other characteristics. Because of this standardization, they can be built in advance of orders, in economical manufacturing quantities, and at low cost as compared with tailor-made methods. The design problem, however, differs in no important respect from that of the single specially-designed machine. The complete machine is the designer's objective in both cases—it is the design unit.

The production problem is also relatively simple and has a well-developed technique back of it. It varies, of course, with the variety of sizes or kinds of product included in the line. We may have one model in a factory or a hundred, but so long as the quantities of each can be established in advance of sales, and the complete machines can be produced for stock, the production problems are of the same nature.

The major problem in this class of product lies between the sales and manufacturing departments. Sales must be confined to standard ratings, and production schedules must be closely aligned with sales —both as to total volume and distribution among sizes and types.

If designs are competitive, if manufacturing practice is efficient and if sales effort is properly directed and coordinated with production, this class of product can be manufactured at surprisingly low costs. This situation may be compared with the ready-to-wear clothing business and, like this business, costs and prices are low, but variety of goods to meet any one customer's requirements is limited. Customers must waive individual preference and special requirements in return for low prices.

Lying between the class of special machines that must be built to order and the standardized product that can be built for stock, is a large and important class of small and medium sized machines that constitute a particularly difficult design and production problem. They cannot be built for stock because of the wide variety of customer requirements, and they are too small to absorb the high special development and labor cost incident to special design and custom building. For this class of product is required a method of design and manufacture that will combine the flexibility possessed by the special built-to-order system and the low cost of the standardized product.

The importance of the problem arising from this class of machinery business is increasing rather than decreasing. The percentage of special machines is increasing, and this is true even in the small motor field, because of the advantages of built-in motors for driving various types of machine tools, woodworking tools and equipment for an almost infinite variety of applications. The outstanding advantage of electric drive is its adaptability to all sorts of mechanical conditions and requirements. The electrical machine designer then must be prepared to meet this demand even at the expense of an increasing ratio of specials to standards. He may regret this tendency, but wisdom requires that he find ways of meeting the new condition with as little sacrifice in manufacturing economy as possible.

Design engineers are finding ways of combining these contrary requirements of flexibility and low cost by the application of the standard-part idea to electrical machine design. Basicly, the standard-part plan means the separation of the machine into parts or elements, some of which can be used in many

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different designs and others of which will generally change with every design. The major mechanical elements, such as frames or pedestal bearings, will obviously be consistant parts that can be standardized or simplified. Windings, in general, will be variable elements that will change with every rating. The purpose of the plan is to reduce the standard parts to the minimum number of sizes and so to organize the methods of design of complete machines that a given standard part will be used in as wide a range of ratings as possible. There is nothing new in the idea itself. Reduced to its simplest form it is the idea, for example, of building an infinite variety of houses from one size and kind of building brick and a small number of sizes of standard doors, window sash, etc. It has been used for many years in control and switchboard building. The new thing worthy of note is the application of this old idea to the internal parts of complicated electrical machinery and in such a way as to meet the exacting performance requirements demanded by the present ad-

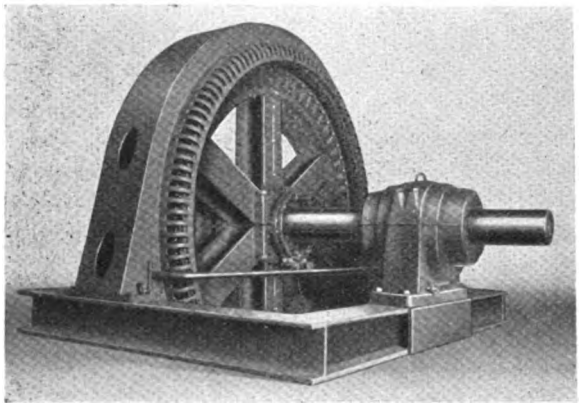

FIG. 1—A TYPICAL MODERN SYNCHRONOUS MOTOR

vanced state of the art. This standard-part idea was first applied to a line of engine-type synchronous motors and generators eight years ago, has been extended slowly and has recently been applied to the more complicated case of commutating machines. The introduction of fabricated construction, referred to later, has increased the possibilities of the standard-part plan tremendously.

SUCCESSFUL application of this idea requires a complete change in the designer's objective and method. He is no longer concerned with the design of single ratings and with the problem of making the best possible design for that rating alone. His unit of design is a single part—frame, main pole, armature punching, commutator and so on. His problem is to design that part so that the desired range of ratings can be built satisfactorily with competitive performance, with the absolute minimum number of sizes of that part and to secure the maximum application of the part. Some parts of the machine will necessarily vary with every rating, but the degree of success attained by the designer will also be measured by the reduction in number of such variables.

Low manufacturing costs result from standardization and mass production. It may not be considered that in the large machinery business we are dealing with sufficiently large volume and number of units to be concerned with mass production methods. The real significance of mass production, however, is not so much quantity of product, as it is simplification of product. The important concept is not so much large quantity as it is small variety. Variety in this connection is small when the factory can visualize its problems in terms of an entire line of machines or parts and lay out its equipment and perform its various functions for the entire line rather than for single designs and customer's orders.

The essence of the standard-part plan of design is so to simplify the product that ordinary mass-production technique can be applied. This technique includes the general use of time-study methods; the complete application of time limits to all operations before production is started; the generous use of tools, fixtures and jigs; specialized machine tool equipment in some cases; a minimum number of set-ups by adopting economical manufacturing quantities; and the possibility of installing a simple cost system whereby standard costs will be available quickly and completely. This is all possible when the factory is dealing with a limited variety of standard parts, but it is entirely out of the question when the same output is produced from individual special designs.

One of the important contributions of design and manufacturing engineers to the solution of this low-profit problem is the development and application of the standard part plan to the building of medium size electrical machinery. The successful application of the plan is an important result of bringing together, in purpose and experience, the design engineer and the factory.

## FABRICATED MACHINES

AN interesting development in heavy machinery construction during the past few years is the use of rolled plates, slabs and shapes, fabricated by gas cutting and arc or gas welding, to replace iron and steel castings. This application of structural material has been particularly desirable in the larger special class of machinery and in the medium size standard-part lines.

The main advantage of this new construction in large special machinery is the elimination of patterns and, to some extent, machining operations, thus shortening delivery time. A stronger and non-breakable construction is obtained in those cases where iron castings are displaced. The uncertainties of large steel castings are eliminated. A particularly valuable feature of fabricated construction in

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machinery of medium and large size is the flexibility of the construction that permits a wide application of any given element of the machine. To illustrate: A frame for a medium-size engine-driven alternator of the fabricated type consists only of two end plates with the core laminations clamped between them. The same size of frame rings can be used for cores from three inches to eight inches or more in width. The only variable parts of the stator are the bolts on which the laminations are built, and the channel stiffeners between frame rings and these parts vary only as to length. Because of this simple and adaptable construction that reduces inactive material and weight to a minimum, it is economical to employ narrow cores and to use many core widths. It also reduces the constant or standard elements of the structure to simple forms that can have wide application. Again, in the application of larger direct-current generators and motors to varied uses and in various mechanical combinations, the distance from the center of the shaft to the bottom of the supporting foot of the frame is different in nearly every case. With cast frames this required a change in the pattern and the production delay incident to procuring special castings. With the structural design the frame feet are welded to the ring and the location can be changed at will.

In direct-current machines, the use of the fabricated construction is justified by this feature of flexibility alone. Ten or fifteen years ago the large volume of business in direct-current machines of medium size was in low-speed engine-driven generators. These were well standardized as to rating and speeds and the most popular sizes were built for stock. Today the low and medium speed machines are purchased mainly for diesel-electric sets for land or marine service, and as constant or variable speed motors. Particular designs are rarely duplicated. To supply this market profitably, the manufacturer must be able to build these special designs with moderate development expense, for drawings, patterns, tools, etc. and within short delivery time. Where delivery time was measured in months, a few years ago, it is now measured in weeks. The fabricated construction plus the standard-part plan of design is the engineer's answer to this difficult production and cost problem.

An existing design using castings cannot be changed over to fabricated construction by simply replacing the casting with an equivalent fabricated structure and obtain the full benefits of the new construction. The entire machine—and preferably the whole line of machines—should be redesigned as completely as necessary to make use of the possibilities of the fabricated construction. Here again best results follow when the designer and factory work together in full accord.

While there are important advantages to be derived from this new construction—advantages that both manufacturer and purchaser will share—these can be realized only by the courageous scrapping of existing manufacturing plant and the installation of new equipment of novel type. In place of the foundry there are substituted the furnaces and bending rolls for the heavy rings used in direct-current frames and alternator rotors and stators; in place of machine tools, the gas cutting machines; and finally, automatic welders, etc. required for fabrication. Lines of machines must be redesigned and old lines scrapped. Thus, there are heavy initial development costs that must be absorbed before the manufacturer can realize savings from the change.

## PROGRESS IN DESIGN

The general subject of materials and how best to apply them is the peculiar field of the design engineer, in his scientific role, and in most presentations of the work of the design engineer this phase of the subject is the one usually given most attention. The outstanding work of the design engineer in reducing size and weight of apparatus and in improving its performance, is so well known and so generally appreciated that it may safely be left to the reader's present general information. One interesting example will, nevertheless, be given. During the past year the construction of the large vertical water-wheel generators for the Conowingo plant of the Susquehanna Power Company has afforded an interesting object-lesson illustrating the contribution of the designing engineer to this low-profit problem.

When that part of the factory at East Pittsburgh, known locally as Section D, was built thirty years ago, it was designed with higher head room than any of the existing buildings, in order to provide for the construction of the 5000 kw, 75 r.p.m. alternators then under contract for the Manhattan Elevated roads in New York City. The frames of these alternators were something more than forty feet in diameter and height. These Manhattan generators and the similar New York Subway generators built a few years later, were the first and the last low-speed engine-driven alternators of this large diameter to be built in this factory. Steam turbine drive then swept the field, and the specially-built factory seemed to have passed its maximum usefulness within a very few years. Within the past five years, however, this high head room has been taxed to accommodate large low-speed alternating and direct-current motors for rolling-mill drive and low-speed vertical alternators for hydraulic-turbine drive. During the past two years the Conowingo generators have been built in this factory and their diameter slightly exceeds that of the old Manhattan alternators. This experience suggests the observation that it is difficult to build too big for the electrical industry in these United States—the industry sooner or later will justify the most ambitious plans—but unfortunately it

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is very easy to build too big too soon, and time is a very important factor in profits.

A comparison of these two alternators—the Manhattan and the Conowingo—spanning a quarter century of design—may be interesting. The first fact of interest is that the output of the Conowingo generators is 40 000 kv-a, while the output of the Manhattan generators was 5000 kv-a. Here is a ratio of eight to one in output with a ratio of only two to one in volume of active material. The machines are compared in Table I.

TABLE I—COMPARISON OF GENERATORS

| | Manhattan | Conowingo |
|---|---|---|
| Rating | 5000 Kv-a. | 40 000 Kv-a. |
| Power Factor | 100% | 80% |
| Voltage | 11 000 | 13 800 |
| Phase | 3 | 3 |
| Cycles | 25 | 60 |
| Speed | 75 | 81.8 |
| Number poles | 40 | 88 |
| Outside diameter, stator punchings | 407 in. | 412 in. |
| Width of stator core | 24 in. | 47.5 in. |

THE question naturally arises as to the reason for this increase of nearly four to one in output-per-pound. It is natural to look first at the magnetic flux density in the core and the current density in the copper circuit for an explanation. Higher densities would, of course, indicate the use of less material. An examination of the two designs shows that the magnetic circuit of the older generator, not the modern one, was worked at appreciably higher inductions in the core. The current density due to useful current alone in the armature winding is thirty per-cent higher in the Conowingo design, but the actual current density, including eddy currents, is very much lower in the modern designs. Neither of these factors, then, accounts for the observed improvement in economical use of materials.

The significant difference in design that does account for this considerable reduction in material is in the so-called armature conductor loading—the number of ampere-conductors employed in the armature windings. There are 3.6 times as many ampere-conductors per inch of armature diameter in the Conowingo design as in the old Manhattan design. This increase in ampere-conductors results in a corresponding decrease in magnetic flux and cross-section of magnetic circuit required for the same rating or a corresponding increase in rating for the same magnetic material. In the modern design, the weight of armature copper per kv-a and r.p.m. is only one-fifth of that in the older generator and the similar ratio for the field copper is something over three to one in favor of the modern design.

These facts mean simply that designers have learned how to load the stator with conductors without getting into trouble from the stray load losses due to eddy currents that would naturally come from the concentration of copper in a magnetic field of high density.

The significant difference in design practice represented by these two generators is shown by the sketches of the two armature slots and the arrangement of conductors in the slot, in Figs. 2 and 3. Deeper and deeper slots with an increasing number of conductors in a slot are characteristic of modern large alternator design, and indicate progress of the designer in eliminating these highly objectionable stray fields and useless circulating currents.

EXAMINATION of these two designs—each typical of its period—shows that the rather remarkable increase in output per unit of material has been accomplished by only two major design developments; and that, in respect to both of these, improvement has come from a long series of small steps rather than from any radically new thing in machinery design. These two developments are the increase in armature conductor loading, and improvements in ventilation and cooling of electrical machinery. The ability to load armatures more heavily comes directly from control of eddy-current losses in

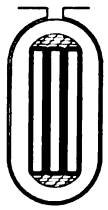

FIG. 2—ARMATURE SLOT OF MANHATTAN GENERATOR

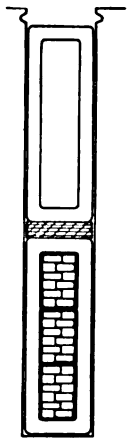

FIG. 3—ARMATURE SLOT OF CONOWINGO GENERATOR

the copper. It is interesting to consider that much of our progress in design of large alternators during the past ten or fifteen years is due fundamentally to the theoretical and experimental work of a small number of engineers who have devoted their labors to the solution of this eddy-current problem.

Another interesting illustration of the advance in alternator design that must be credited to the control of eddy-current losses in armature windings is afforded by the reconstruction of the early Niagara generators. These generators were built in the early nineties and reconstructed to change the phase and voltage in 1922.[4] The improvement in design is evident from Table II.

If this question of the effective use of materials is considered broadly it is seen that the size and weight of an electromagnetic machine depends on three major factors:—

1—The physical, electrical and magnetic properties of available materials. In respect to only the first of these—

[4]For details of this reconstruction see article by M. W. Smith in JOURNAL for August 1922, p. 342.

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physical properties—have important improvements in materials been made. In respect to magnetic properties there have been important developments with regard to losses, but not with regard to permeability, which would permit the advantageous use of higher magnetic densities.

2—Ventilation.

3—Armature-ampere-turn loading.

## RESEARCH AS A FACTOR IN DESIGN

In this day it is unnecessary to stress the business value of research as the foundation of, and as an adjunct to the work of the design engineer. But the connection between research and large machinery design may not be as obvious as in some other fields of work. With radio sets and tubes, tungsten lamps and similar devices, the dependence of design on research is a matter of common knowledge. Large machinery design, on the other hand, is not so subject to revolutionary changes; types are well established and methods and proportions change only in detail. Research in the fields of chemistry and physics does not apparently supply any need in the development of heavy electrical machinery. Only a few years ago this was the situation, but with a better appreciation by design engineers of the facilities of the research laboratory and of the kind of training and experience possessed by the research staff,

TABLE II—COMPARISON OF DESIGNS

| | Original Design | As Re-Built |
|---|---|---|
| Kv-a rating | 3750 | 5000 |
| Volts | 2200 | 12000 |
| Load loss—kw. | 210 | 17 |
| Decrease—kw. | | 193 |
| Total Losses—kw. | 344 | 148 |
| Decrease—kw. | | 196 |
| No-load core-loss—kw. | 41.2 | 32.5 |

there has developed a close and active personal contact between the scientific staff of the research department and the designers of large machinery. The imperative urge toward lower costs developed by present low-profit markets has been an important factor in bringing about this closer co-operation. The design engineer must develop in two rather diverse directions—toward the more practical business side, represented by the factory, and toward the scientific phases of his work as represented by research.

A few examples of the kind of problem the research man may solve for the design engineer will help make this picture more definite. In the design of a turbine generator—the largest 1800 r.p.m. generator yet undertaken—a new type of rotor ventilation was suggested, but this proposed design increased stresses in the rotor teeth. The complicated shape of the parts and the nature of the stresses involved made it impossible to calculate the actual distribution of the stress. At this point the designer, if he had no more than ordinary facilities, would have been forced to conclude that the uncertainties of the situation were such as to make the proposed design too risky. This is where the physicist stepped in. By means of experimental methods and equipment which have been developed during the past few years, the stress distribution in any complicated structure can be determined visually by passing polarized light through celluloid models of the part in question. This investigation was made in the case of this particular turbine generator problem and the proposed ventilation scheme was found to be safe and practicable. This is an example of how the improved experimental methods and equipment of a modern research department can be of direct benefit in the design of an individual machine.

For many years certain types of large water-wheel generators have been built with laminated rotor rims. The mechanical design was based on certain arbitrary assumptions as to the behavior of this built-up structure when highly stressed. The correctness of these assumptions was questioned, and the problem of determining just what happened at overspeed was put up to the research department. They constructed small models involving the same elements as the large laminated rim spider and determined, by means of very exact measurements of the distortion of the models under stress, the real nature of the stresses involved and their effects on the structure. With this knowledge, furnished the designer by the research department, it is possible to considerably improve the design of this part and meet the demand for larger units or higher overspeeds.

A number of years ago there developed serious trouble caused by the swelling of armature coil insulation in some large turbine generators. When this trouble first appeared, tests were conducted by the designing engineers using the available facilities in the factory and the worst of this swelling was eliminated. Some tendency to swell remained and was a source of potential trouble. About two years ago this general problem was given the Research Department and with characteristic thoroughness they determined to find the fundamental cause of the swelling. As a result of this basic work by a trained chemist an entirely different bond was developed that practically eliminated the cause of insulation swelling.[5] This is an illustration of another type of work done by the research department for the benefit of the design engineer.

This list of examples could be continued indefinitely, but these few will serve to show the close connection between the work of physicists and chemists in the research laboratory and the everyday work of the designing engineer. The research staff and the research laboratory have become effective allies of the engineer in his task of meeting the ever-increasing needs of the industry.

[5]For details of this work see a paper by Dr. C. F. Hill, presented at the Baltimore Meeting of the A.I.E.E., April 17, 1928.

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# 165 000-Kw Turbine Generator for Hell Gate

H. J. HANZLIK
Engineering Department,
South Philadelphia Works,
Westinghouse Electric & Mfg. Co.

THE new 165 000 kw steam turbine generator, to be installed as No. 9 unit in the Hell Gate Station extension of the United Electric Light & Power Co., New York City, is rapidly nearing completion. This will be the largest two-cylinder compound generating unit in the world. Some years ago this station was started with the installation of a 40 000 kw unit. Subsequently the station capacity was increased by the addition of three 35 000 kw units, a 40 000 kw unit and two 50 000 kw units. The 160 000 kw and the 165 000 kw units now on order will permit 610 000 kw to be developed at this station, which will then be the largest generating station in the world.

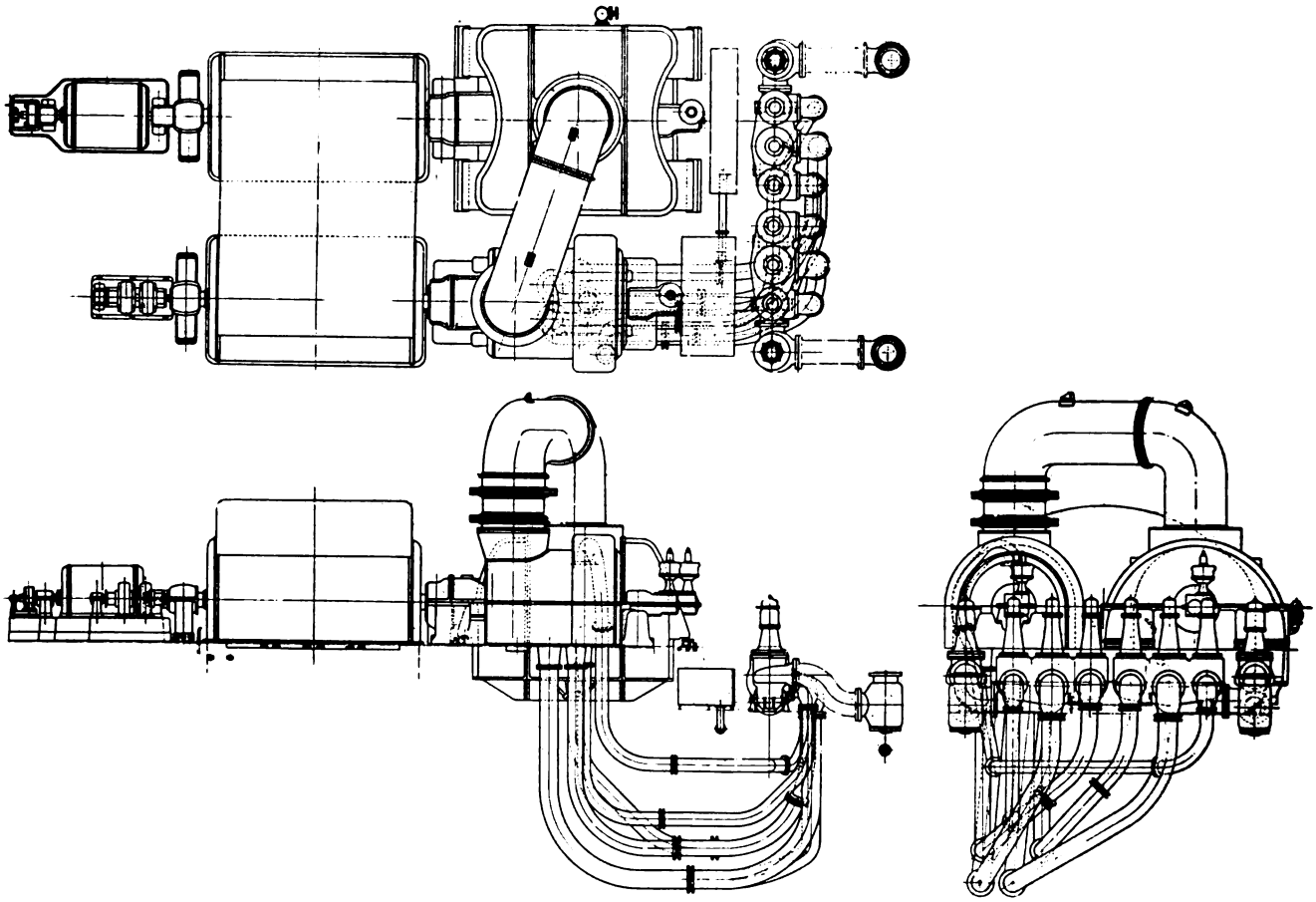

FIG. 1—OUTLINE OF 165 000 KW TURBINE GENERATOR FOR HELL GATE POWER PLANT

The present 165 000 kw unit is of the two-cylinder cross-compound design. The high-pressure element drives one main generator and is also coupled directly to two 200 kw, 250 volt exciters, each exciter serving one of the main generators. The low pressure element drives one main generator, one 5000 kw, 2400 volt auxiliary generator and one 50 kw, 250 volt direct-connected auxiliary generator exciter. Each of the two main generators has a rating of 94 200 kv-a, or 80 000 kw at 85 percent power-factor, 13200 volts, three-phase, 60 cycle, 1800 r.p.m.

Each stator frame is of welded steel construction throughout, and each frame is built in two annular sections with the split between the sections coming at right angles to the longitudinal axis of the generator. Low loss punchings of the ordinary thickness make up that portion of the magnetic circuit contained in the stator.

The two main generators will be enclosed in a common sheet steel superstructure which will form the cooling air passages. Lifting of a generator will be accomplished by means of removable trunnions. The frame feet which support the stator on the foundation are made removable in order to keep the dimensions within the limits of railway clearances.

The armature windings are composed of diamond type coils made in halves. These coils are thus constructed in order to facilitate handling of masses of such magnitude. Transpositions are carried out in the straight part of the coil halves. The coils have each strand insulated by mica tape. The wrapper is of mica folium bonded by an asphaltic gum recently

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developed. Under test, coils held by this bond showed inconsequential values of swelling and approximately one-fifth the value of dielectric loss experienced with coils held by other adhesives.

The rotor is of the usual plate construction, composed of shaft ends, several plates, and the through bolts. The shaft ends which make up the steps of the rotor between the journals and the full diameter of the rotor body are made of high test nickel steel forgings. Between the shaft ends are placed a series of specially forged carbon steel plates. The shaft ends and plates are held together by four high-strength alloy steel bolts located one in each pole center.

The straight part of the winding on the rotor lies in mica cells in the rotor body. Each successive turn in the slot is insulated by means of a mica strip. In order to protect the rotor and windings against insulation failure, they are contained in a new type of channel insulation. The channels are made of molded asbestos shaped to interlock and prevent the accumulation of dirt deposits. Rotor ventilation is accomplished by means of several parallel air paths so that the conduction is directly from the seat of the losses.

Adequate cooling of the central portion of so long a stator introduced an interesting problem in ventilation. Approximately 275 000 cu. ft. of air per minute is delivered into a common duct, which leads into both main generators from three external high efficiency vertical propeller-type motor-driven blowers. These blowers will be centrally located below the main generators. The cooling air is discharged from the top of the blowers and after passing through the generators enters the air coolers and thence re-enters the blowers. The blowers are each directly connected to a 300 hp induction motor, which operates at 3520 r.p.m. The three blowers including their drives occupy a floor space of only 5 ft. by 17 ft.

The total weight of the complete turbine generator unit is approximately 1300 tons; 700 tons for the turbine and 600 tons for the generator.

Steam will be supplied to the high-pressure turbine element through two lines, each connected to a 28 inch steam strainer, throttle valve and a three-valve steam chest and thence through a number of flexible loop pipes, located below the floor before entering the high-pressure cylinder. Steam at 265 pounds gage pressure, and 700 degrees F total temperature will be supplied and will be discharged to the condenser at a pressure of one inch mercury absolute. The turbine is designed for steam extraction in two stages, which will heat the feed water in two surface heaters from 77 degrees F to 252.5 degrees F at maximum load.

The high-pressure element is of the single-flow type having a two row impulse wheel together with 14 pairs of rows of reaction blading. The low-pressure element is of the double-flow reaction, multi-exhaust design and has seven pairs of rows of reaction blades on each side of the steam inlet. The last two pairs of rows in this turbine include blading of the multi-exhaust design. All blades are of polished stainless steel.

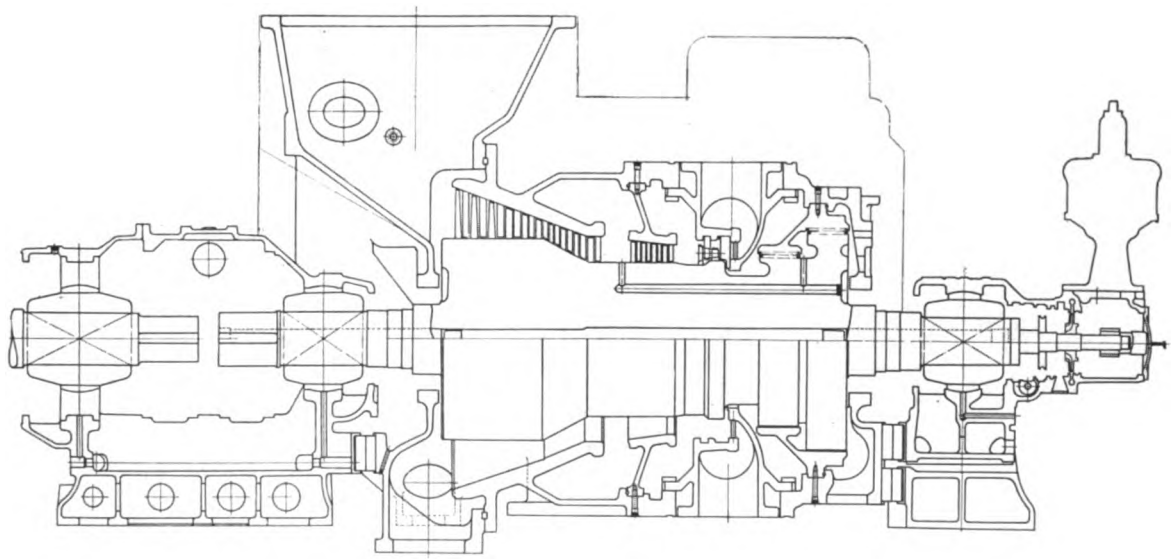

FIG. 2—LONGITUDINAL SECTION OF HIGH-PRESSURE ELEMENT FOR 165 000 KW TURBINE GENERATOR

The high-pressure cylinder is made in two parts. The thrust end, carrying the nozzle chamber, the dummy and one blade ring is made of cast steel. The coupling end of the cylinder does not contain any blades and is made of cast iron. Each cylinder has two feet resting on pedestals. Each of these feet is provided with a holding down bolt and a pipe spacer, so that each cylinder foot can expand freely in all directions. The purpose of these bolts is to resist the reaction torque, when the turbine is running.

The high-pressure cylinder is tied to the coupling end pedestal by means of two axial pipe struts, the coupling end pedestal being grouted to the foundations. The thrust end of the cylinder is connected by

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two pipe struts to the thrust end bearing housing, which slides on the thrust end pedestal, when the cylinder expands. The thrust end pedestal is grouted to the foundation. The cylinder is located transversally by means of vertical keys, which permit vertical and axial movement, but prevent displacement in the transverse direction. There is one key at the coupling end and there are two at the thrust end, one engaging the pedestal and the other engaging the bearing housing.

The blade and dummy rings are set in circular grooves, their steam joints being protected by standard construction. The blade and dummy rings are supported from a point close to the horizontal joint in order to preserve the concentricity of the rings when the turbine is hot. Dowel pins at the top and bottom hold these rings to their seating joints.

In the region of high pressure and temperature, the two halves of the cylinder are held together by special steel studs. These studs have their centers drilled with stepped measuring holes that permit insertion of a heating element to give the stud proper stretch and to permit entry of a special micrometer to measure the predetermined stretch of the stud.

The high-pressure cylinder, steam pipes and valve gear are provided with standard insulation. Joints that are removable have special insulation blankets that permit easy access to bolts and nuts. The insulating material is enclosed under a steel jacket. This jacket is so divided as to permit easy removal of glands and cylinder cover.

Water glands are provided, each consisting of water runner vane segments mounted on a sleeve. This sleeve is provided with a vertical face flange, bolted

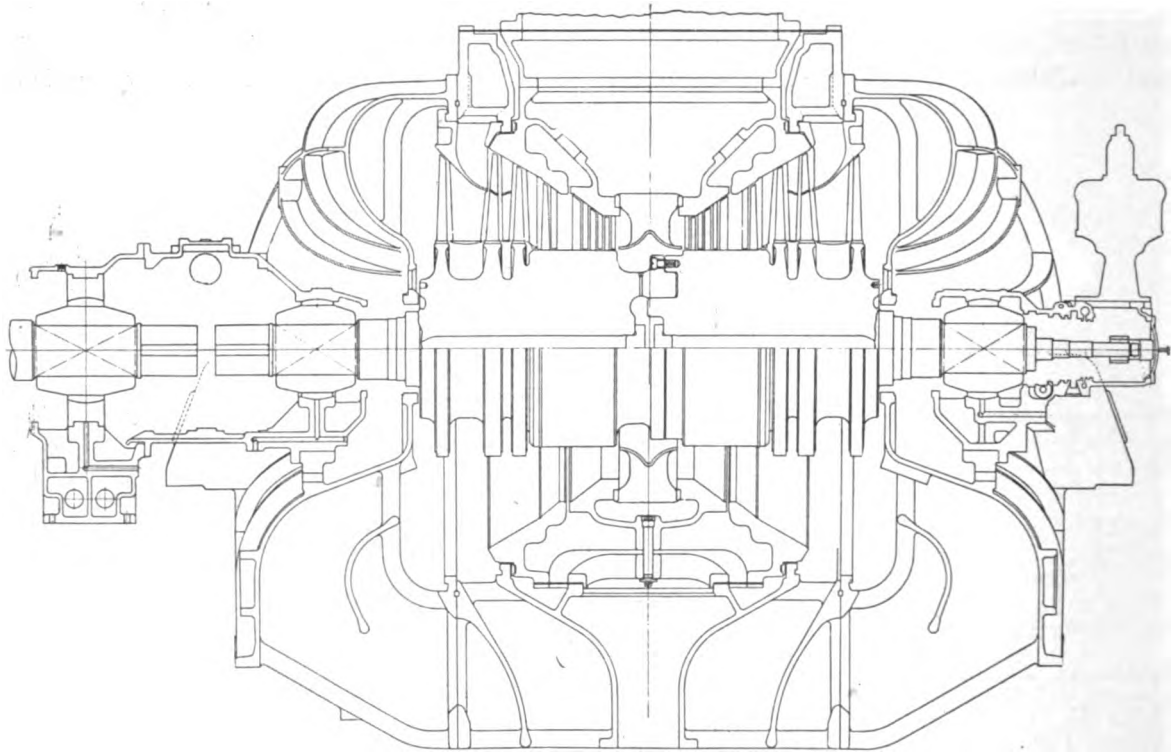

FIG. 3—LONGITUDINAL SECTION OF LOW-PRESSURE ELEMENT FOR 165 000 KW TURBINE GENERATOR

The primary and secondary nozzle chambers are located in the base and cover of the thrust end of the cylinder and have a series of circumferential feet resting on bored supports in the cylinder. These chambers are located in the axial direction by means of circumferential tongues and grooves and are held in correct radial location by a radial key and clamp, arranged at the inlet of the nozzle chamber, permitting free expansion of the nozzle chamber from this key point. The inlet openings to the nozzle chambers are short flanged nozzles with the machined faces in the same plane as the corresponding flanged faces on the outer cylinder wall. A thin metal diaphragm plate is bolted to the main cylinder structure and to the nozzle chamber to seal against steam leakage from the impulse chamber and at the same time to allow free expansion of the nozzle chamber.

onto the spindle, thus eliminating the possibility of air leaks along the shaft. Water passes through two annular channels located at the outer periphery of the runner and flows from the inside out. A sufficient amount of water is circulated through the glands to reduce to a minimum the amount of water evaporated from the rotating water seal.

The spindle is a single forging with a short extension at the thrust end. This extension carries the thrust collar, main centrifugal pump impeller, governor worm gear and automatic stop. The forging is the largest spindle forging ever produced. The spindle is fitted with a two step radial-contact dummy. The steam that leaks from between the two dummies is carried to a point between the first and second reaction elements through a number of holes in the spindle. Steam passing through these passages tends to keep

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the spindle body uniformly heated. At the same time the steam is returned to a point where it cannot mix with wet steam that is being bled, but it is turned into useful work.

A central inspection hole was bored from end to end of the rotor. A thorough examination of the interior of the forging was made with a special telescope instrument. A similar procedure was applied to the low-pressure spindle forging.

Between the oil rings and glands provision is made for attaching spindle truth indicators, to indicate the amount that the spindle goes out of true, when it is heated or cooled off. To keep the spindle straight during shut down periods, air nozzles are provided in the cylinders, by means of which air may be circulated inside of the cylinder to keep the temperature uniform around the spindle. There is also provided a motor-operated turning gear by means of which the spindle may be rotated at slow speed during shut down periods in order to insure uniform cooling of the rotating element. In this manner it is possible greatly to reduce the time required to bring the turbine up to speed when starting again.

Steam leaving the high-pressure turbine enters the low pressure turbine through an overhead receiver pipe and expansion joint. The receiver pipe is 82 inches in diameter, and is made of steel plate with welded joints. It is reinforced by built-up, welded I-beam sections bent around the circumference at several places to prevent collapsing due to atmospheric pressure when running at light loads. The maximum temperature in the pipe is normally about 335 degrees F. and the transverse expansion is taken care of by an expansion joint consisting of four diaphragms that are distorted when full expansion or full contraction takes place. The expansion joint is braced by two powerful links placed diametrically opposite and parallel to the axis of the joint. They resist the bursting forces inside of the joint. Water sealing is not employed.

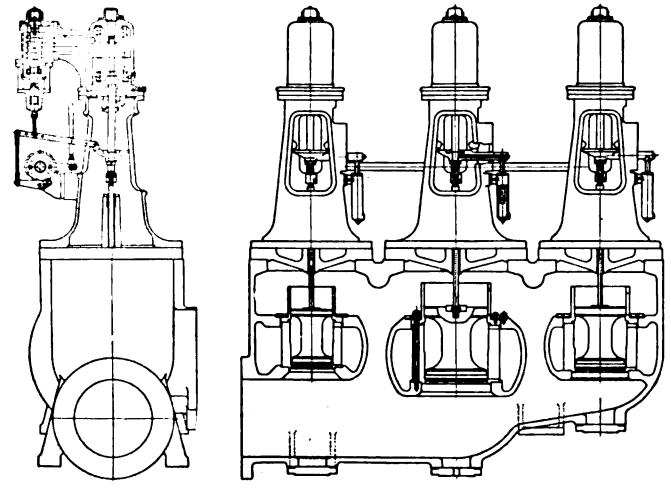

FIG. 4—THE CONSTRUCTION OF ONE OF THE TWO DUPLICATE STEAM CHESTS

The low-pressure cylinder consists of three outer parts; thrust end, center and coupling end. These three outer parts enclose a loose blade ring which carries all of the stationary blades except the last row at each end. These are supported by the cylinder ends. The outer cylinder parts enclose the vacuum side of the turbine and, therefore, are cool. To this cool outer structure are attached the cylinder feet, which rest on adjustable wedge blocks.

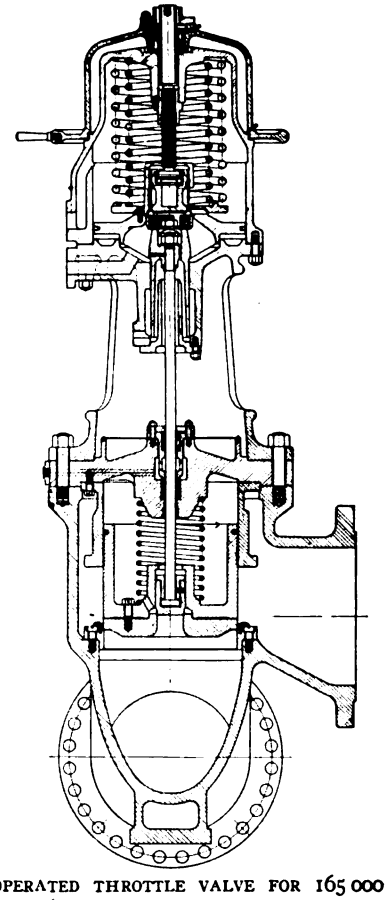

FIG. 5—OIL OPERATED THROTTLE VALVE FOR 165 000 KW TURBINE GENERATOR

The cylinder blade ring is supported by the outer cylinders from a point close to the horizontal joint to maintain concentric alignment of the blades, when the parts are heated. Vertical and axial location of the blade ring is secured by adjustable brass liners. Transverse location of the blade ring is maintained by means of a king pin at the bottom of the blade ring. Expansion of the blade ring at the steam inlet end and its expansion at the bleeder outlet is taken care of by copper expansion joints of the diaphragm type, which permit some movement of this blade ring up and down from its supports.

The blade ring is provided at the inlet end with cast steel guide vane segments, that guide the steam efficiently into the blade ring and at the same time act as struts to resist the atmospheric crushing pressure that is transmitted from the cylinders onto the blade rings when running condensing. At each exhaust end of this blade ring there are spacing washers with proper clearance to permit expansion of the blade ring in the axial direction, without exerting excessive pressure on the main outer cylinders. By means of this

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clearance this outward expansion is carefully compensated by the atmospheric pressure from outside. The blade ring has two annular bleeder chambers that lead wet steam down through the center cylinder base through the condenser "Y" discharge pipe and into a 12 inch bleeder pipe in the low-pressure heater system.

The cylinder ends and center are provided with stream line vanes, that guide the exhaust steam into the condenser smoothly, avoiding sharp turns in order to obtain the most efficient steam flow. The exhaust end base is bolted to the coupling end pedestal which is grouted in, forming an anchor for the low-pressure turbine. The thrust end pedestal is not supported from the foundations but is bolted directly to the cylinder base. This cylinder base is located in the transverse direction by means of a sliding key, anchored to the cross girder of the foundation at this end.

The spindle of this double-flow turbine is made in two pieces about equal in size, with a small shaft extension at the thrust end. Each forging has an inspection hole bored from end to end. These holes are covered at the inside end by flanges, to prevent heating of the journals. The size of the spindle is such. that it can be shipped, assembled and bladed. This is of considerable advantage, as it eliminates the necessity of taking apart for shipment and subsequently reassembling in the field. The bladed spindle can, therefore, be installed in the condition it is in after it has been seasoned in the heater box. Two rows of tapped holes are provided on each end of the spindle for balancing. The inner ring of holes are used for shop balancing and the outer holes for field balancing.

All the blades are made of polished stainless steel. The last three rows on each end of the spindle are of the new side-entry type that permits lighter design of the spindle and facilitates removal of individual blades. The side entry blades have a curved root of serrated section. The curvature of the root conforms with the curvature of the blade body, permitting a good distribution of centrifugal forces over the blade fastening. The lower part of the blade root is rolled over the spindle rim at the ends to prevent any tendency of the blades to slip out endwise. All the blades are lashed to reduce vibration. Long blades are tapered towards the tip to reduce centrifugal stresses, and the cross-sections are warped to secure the best possible steam flow. The last rows of blades are so arranged that part of the steam, after passing through the next to the last row, is deflected into the exhaust chamber while the remainder undergoes further expansion in the last row. In this manner a large exhaust annulus is obtained, for the given blade height and rotor diameter.

The governing system consists of two standard fly-ball governors, one driven from the high-pressure and one driven from the low-pressure turbine. The high-pressure governor operates all six valves in proper sequence with a speed variation of four percent for all valves. The speed changer spring provides an adjustment of plus or minus five percent of no load speed. The fly-ball governor on the low-pressure turbine acts as an overspeed governor. It is set to operate at 10 to 11.5 percent overspeed to close the main governing valves. Besides these flyball governors, each spindle is protected by a standard automatic stop governor. If either of the spindles overspeeds its autostop governor will act to close all six governing valves and the two throttle valves.

The sleeve of the high-pressure governor is connected to an oil relay, which actuates a rock-shaft-operating piston. This operates a rock shaft running parallel with the axis of the steam chests. On this rock shaft there are located six cams each engaging a three inch oil relay. Each relay controls an operating piston, one for each main governing valve. The six governing valves are located in two parallel flow steam chests and are arranged in parallel with each other. The valves are of the standard double ported poppet and balanced type and are seated in forged steel cages. These cages have at their lower end several V-shaped ports to improve regulation at light loads.

Steam is brought to the two steam chests through two 28 inch basket-type strainers and two 28 inch throttle valves. From the steam chest, the steam passes through a number of flexible steam pipes located below the floor into the high-pressure cylinder. Each steam chest body is anchored at one point close to the turbine cylinder and is permitted to slide with its throttle valve in a direction perpendicular to the axis of the turbine.

The throttle valves are of the standard oil-operated type. These valves are unbalanced when closed. by reason of the steam line pressure having access to the chamber above the steam balance piston. On opening the valve, the steam pilot valve opens, first releasing steam from above the piston, permitting the valve to become nearly balanced. The valve stem is operated by a direct-connected oil piston located above the throttle valve body. This operating oil piston is pressed down by two powerful coil springs, that are resisted by oil pressure underneath the piston. The space above the oil piston where the springs are located is connected to the drain tank. To open the throttle valve. the hand wheel stem is screwed down on the pilot valve and the oil pressure is established below the oil piston. This may be done as soon as the auxiliary oil pumps are brought up to speed. The hand wheel is then turned so as to move its stem upward. The pilot valve, pilot valve seat and piston will then follow this movement, forced up by the oil pressure under the piston. The throttle valve body is of the stream-line-flow type that will pass the steam with least drop in pressure.

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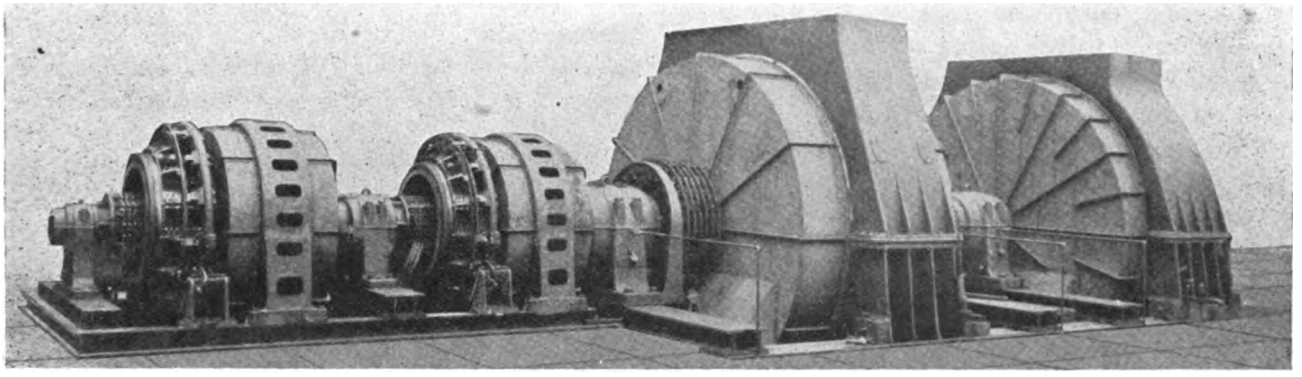
**Fig. 1—A 20 000 Kw Variable-Ratio Frequency-Changer Set, interconnecting the 25 and 60 cycle systems of the Niagara, Lockport & Ontario Power Company at Lockport, N. Y.**



# Variable-Ratio Frequency-Changer Sets

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Motor Engineer,
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With the development of the long distance power systems, there has been a large increase, both in the number of ties between different systems, and in the rating of the units employed, due to the increased capacity of the systems. The synchronous-synchronous type of frequency-changer set has been used almost exclusively until recently, when the variable-ratio frequency changer was brought out to fill a limited number of applications where a synchronous set was not particularly adaptable.

With a fixed tie—i.e. a direct line where voltages and frequencies are the same; transformers where the voltages are different and the frequencies are the same; or synchronous-synchronous frequency changers where the frequencies are different—both systems must maintain their frequencies. If one system speeds up, the other must follow, if the tie is to remain intact. Any tendency on the part of one system to change, will cause a change in the amount of power through the tie until conditions of equilibrium are reëstablished. The tie must be of sufficient capacity to permit sufficient interchange of power to satisfy this condition.

With synchronous frequency changers, experience has shown that there is a certain minimum size of set which will successfully tie two systems together and allow them to ride through minor system disturbances without pulling apart. For systems with a preponderance of steam turbine-driven generators, this minimum size is 10 to 15 percent of the generator capacity in operation on the smaller system. For hydro-electric systems the values should be increased to 15 to 20 percent, because of the greater sluggishness of water-wheel governors. For less accurately regulated prime movers or for special conditions of load or system operation, it may be necessary to increase this value still further.

With the synchronous-synchronous set the magnitude and direction of power flow through the interconnection can be controlled only by manipulating the prime-mover governors on one or both systems. It is not practicable to attempt to control the power flow accurately or keep it at a constant value.

In most of the applications encountered, the disadvantages are not considered important, and the synchronous set will serve the application admirably. The variable-ratio frequency changer was developed to suit the cases where the following features are desired:—

1—When the amount of power to be transferred is less than the 10 to 20 percent of the smaller system.

2—When control of the direction and magnitude of energy transfer is desirable directly at the set.

3—When it is desired to maintain the transfer of energy at a constant value.

4—When the system loads fluctuate widely, or the system frequencies are not closely maintained, so that the use of a synchronous set is questionable.

After the description of the various types of variable-ratio sets which is given below has been studied, it will be apparent that the advantages of these sets cannot be obtained without certain disadvantages. A careful and complete comparison should be made before a decision is reached in favor of the variable-ratio frequency changer. The disadvantages of this set may be summarized thus:—

1—Because of the auxiliary equipment needed, the efficiencies of the variable ratio sets are lower, perhaps 1.5 percent in some cases.

2—For the same reason, the initial cost will be higher than a synchronous set of equal rating.

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3—Greater floor space is required, and greater weights accompany the greater amount of equipment.

4—Maintenance costs will be greater, particularly since some of the machines are commutator machines.

However, several sets of this type are now in operation, and for that reason, if for no other, a description of the various schemes which may be used will be of value. Most of the sets built to date are of the third class listed as the "alternating-current commutator type".

Variable speed usually brings to mind direct-current machines, but the ratings desired in these units are larger than direct-current machines have ever been built and, moreover, the total power would have to be converted from alternating to direct-current and back again. The efficiency would be low due to this double conversion, and the first cost would be excessive. Induction motors can be built for large ratings and these, when combined with some sort of secondary control, seem to offer the only method available.

The torque developed between the stator and the rotor of an induction motor is proportional to the field strength, and the rotor current in phase with it. Each value of rotor current has a corresponding value of stator current (assuming that no changes are made which affect the power-factor characteristics). The field strength is constant with constant line voltage. Hence a given value of current taken from the line at constant voltage means constant power from the line and the motor delivers a constant value of torque.

The voltage and frequency induced in the rotor are proportional to the relative speed of the stator field and rotor, i.e., at standstill the frequency is line frequency, and the voltage depends on the ratio of turns in primary and secondary just as in a transformer. As the rotor speeds up, its relative speed decreases in relation to the stator field, which is at synchronous speed, and thus the frequency and voltage induced in the rotor winding decreases to zero at synchronous speed, when the difference between the speeds of the stator field and of the rotor is zero. At speeds beyond synchronism, the frequency again increases and the voltage increases but in the opposite sense.

If a certain fixed value of current is assumed to be taken from the line, the motor is receiving from the line a constant amount of power, but is delivering in mechanical energy a constant torque which, with adjustable speed, produces a mechanical output in proportion to the speed to which it is adjusted. The difference between the power received from the line and that delivered as mechanical power to the shaft appears as electrical power at the collector rings (losses neglected). At standstill, the electrical output from the rotor is the full stator input (losses neglected). At synchronism it is zero, and above synchronism it changes to an electrical input. The value of current in the rotor circuit is determined by the torque delivered by the motor, and the voltage is proportional to the difference between the operating speed and synchronous speed.

The usual method of speed control is to use a resistance in the rotor-circuit. In order to carry the load, a definite amount of rotor current must flow through the rotor circuit, but when a resistance is added to the rotor circuit, the current and consequently the torque is momentarily reduced. This causes the rotor to slow down but, as it slows down, its relative speed with respect to the field (rotating at synchronous speed) is greater and more voltage is induced in the rotor circuit which increases the rotor current. This continues until enough current is flowing to develop the necessary torque, but the speed is lower than before.

It is evident that the voltage at the collector rings, required to circulate the rotor current through the external resistance, increases with the amount of resistance used, and more resistance means a lower speed, assuming the same current throughout. At the same current, the power lost in resistance is the product of current and voltage, and in large machines is worth saving.

Instead of producing the voltage at the collector rings by a drop across a resistance, it is better to use a machine which will convert this power into some other form so that it can be used or returned to the line. If the voltage of this machine acted in the same sense as the resistance, i.e., opposed the voltage from the rotor windings, the speed would be reduced and the auxiliary machine would be receiving power, i.e., acting as a motor. If the voltage of the auxiliary machine helped the rotor voltage, it would be operating as a generator and supply power to the main machine and the main motor would operate above synchronous speed.

Assuming a constant torque load on the main machine, the current at the collector rings has a constant value; the voltage, the frequency and the amount of power increase in proportion to the speed variation from synchronous speed, either above or below. Therefore, the machine which uses this energy must be capable of operating on a variable voltage and frequency and, in order to use this most effectively, should run at some constant speed. This means that a commutator must be used.

These machines may be divided into groups depending on how the surplus rotor energy is utilized or converted.

1—The Kramer type of speed set converts the excess rotor energy into direct current using a synchronous converter.

2—The frequency converter type of speed set converts the excess rotor energy either to line frequency or to a frequency in proportion to the rotor speed.

3—The alternating-current commutator machine type of

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speed set converts the excess rotor energy to mechanical energy.

In all of these types the excess rotor energy after conversion may be applied directly to the main motor shaft for constant horse-power outputs, or it may be returned to the line through suitable conversion apparatus for constant-torque outputs.

1—The main set of the Kramer type consists of a synchronous generator, an induction motor, and a direct-current motor, while a synchronous converter on a separate shaft is required in addition. The generator and induction motor are of full capacity, but the size of the direct-current motor and the synchronous converter is determined by the maximum difference in frequencies of the two systems in relation to the normal speed of the set. The rating of the regulating equipment is determined by the pole numbers chosen and the limits when one frequency is at a minimum and the other at a maximum. These may be as high as ten percent of the rating of the set when either system frequency is not held very close, but can be materially reduced

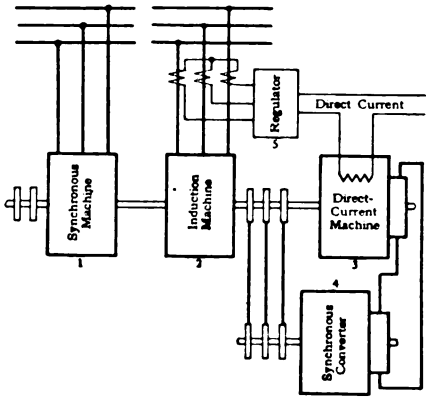


FIG. 2—A SCHEMATIC ARRANGEMENT OF THE KRAMER SPEED CONTROL SYSTEM

where both systems have close frequency regulation.

In Fig. 2, the synchronous generator 1 is connected to one system; the induction motor 2 mounted on the same shaft is connected to the other system. The pole numbers are chosen to agree with the frequencies of the two systems as near as possible and still use as high a speed as practical for the size of the set. The collector rings of the induction motor are connected to the collector rings of a synchronous converter 4. This converter rotates at a very slow speed, determined by the slip frequency, and delivers direct-current on the commutator side. The direct current from the converter is fed to the direct-current motor 3 mounted on the same shaft as the main set and is converted to torque on the set shaft. The speed is regulated by varying the field strength and consequently the voltage of the direct-current motor 3. A regulator 5, actuated by currents in the leads of the induction motor 2, can be used to vary the direct-current motor excitation and thus hold constant load on the main motor, i.e., after the regulator is set, a rise in load on 2 causes less resistance to be inserted in the direct-current motor field and hence raises its voltage, which has the effect of slowing the induction motor and thus deliver less load to the generator. If less load is taken, the action of the regulator is in the opposite direction and the speed and load is increased. Power-factor is controlled by the excitation of the synchronous converter field.

This type of set is not practical for frequency changer application due to the large ratings of the main units, coupled with the fact that this set works only below synchronism and is not operable nearer to synchronous speed than approximately five percent as the converter falls out of step on very low frequency. All the range is on one side of synchronism, so that the auxiliary machines in these sets have twice the rating of other sets which can operate above and below synchronism. The maximum frequency on the rotor is so low that the converter is very large for its rating, which increases the first cost.

A modification of this set makes the direct-current motor a part of another set, which delivers the excess power to the line. This adds one more machine and adds to the cost in most cases.

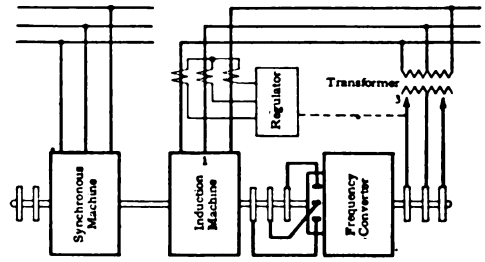


FIG. 3—A SCHEMATIC ARRANGEMENT OF THE FREQUENCY-CONVERTER METHOD OF SPEED CONTROL

2—In the frequency-converter type of speed set the rotor energy is converted into alternating current of approximate line frequency, instead of direct current, as in the Kramer set. Here, also, the converted alternating current may be returned to the line or supplied to an auxiliary motor on the set shaft.

The frequency converter consists of an armature built like a synchronous converter. The stator has coils for commutation purposes only and no torque producing winding. At synchronous speed it develops direct current on the commutator, but since it has no direct-current excitation on the stator and has three or six brush arms per pole pair on the commutator side, it may run at speeds different from synchronism and deliver frequencies in proportion to the drop from synchronous speed on the commutator end. But just as in a converter, the voltage on the commutator is proportional only to the voltage applied to the collector rings and not to the speed or frequency.

In Fig. 3 the frequency converter is on the same shaft as the main motor and so must have the same number of poles in order that the frequency on the commutator will always be the same as that on the induction motor collector rings to which it is con-

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nected. The collector rings of the frequency converter have line frequency on them and are excited from the line through taps on the transformer 3 which are changed automatically by the regulator in response to changes in load on the main machine 1. The transformer 3 may be replaced by an induction regulator or a synchronous motor-generator set if fine steps in voltage are necessary.

The adjustable voltage applied to the collector rings of the frequency converter is transformed in frequency (but not in amount) to the same as the rotor of the induction motor. This causes the motor to change its speed in the same manner as described before.

In Fig. 4, the frequency converter is driven by a separate synchronous motor, so that its speed can be made to suit its own most suitable conditions and not be dependent on the main motor speed. In this scheme, the collector rings of the frequency converter are excited from a synchronous machine on the main motor shaft, which has the same number of poles as the main motor. This machine generates a frequency proportional to the speed of the main motor, which is proportional to $1 - s$ for below synchronous speed and $1 + s$ for above synchronous speed. The frequency converter is driven at synchronous speed so that the frequency on the commutator is proportional to $1 - (1 - s)$ or $s$ for below synchronism and $1 - (1 + s)$ or $-s$ for above synchronism, which is the same as that in the main motor rotor winding.

Voltages induced in the synchronous machine winding by varying the excitation appear on the commutator of the frequency changer, and hence add or

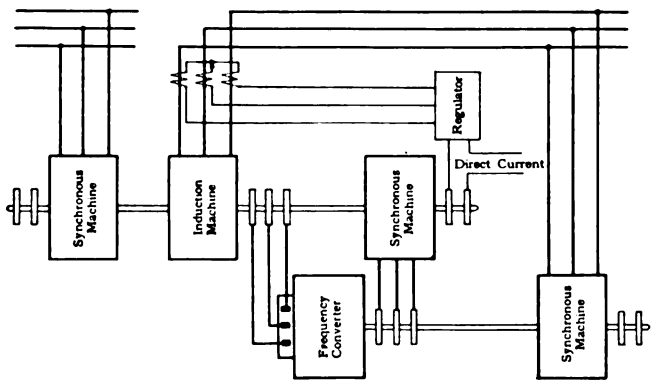


FIG. 4—THE SAME GENERAL SPEED CONTROL SCHEME AS SHOWN IN FIG. 3 EXCEPT THAT THE FREQUENCY CONVERTER IS ON A SEPARATE SHAFT

subtract from the induced rotor voltages of the main motor and cause speed changes as described above.

The above speed changes are accomplished by adding or subtracting a voltage in the same direction as the induced rotor voltage, i.e., where the sum or difference is arithmetic. If another voltage at right angles to the first voltage is applied at the same time, an effect on the power-factor of the unit is produced, which may be either leading or lagging, depending on the direction of the voltage. Instead of two separate voltages, these may be combined into one voltage of the correct phase angle. This may be accomplished either by shifting the brushes or by varying the phase of the voltage applied to the collector rings of the frequency changer.

These sets operate on both sides of synchronism, so that for a given speed range, the rating of the

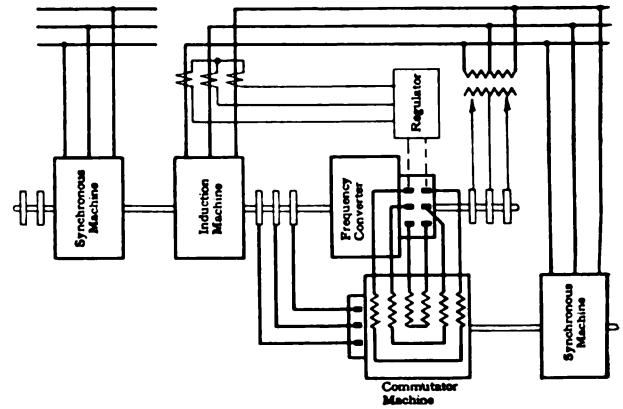


FIG. 5—A SPEED CONTROL SCHEME IN WHICH THE COMMUTATOR MACHINE IS EXCITED ON THE STATOR BY MEANS OF A SMALL FREQUENCY CONVERTER (SHERBIUS SCHEME)
The regulator shifts the brushes on the commutator through a pilot motor.

auxiliary set is one half as large as it would be if the range were only below synchronism.

3—The third type of set converts the electrical output from the main motor rotor directly to mechanical power, which is used to drive an auxiliary machine or is applied to the main motor shaft. The commutator machine is often a part of a separate set, so that it can be designed for its best proportions. The energy from the induction motor rotor is delivered to the commutator usually through a compensating winding, which leaves the machine without a resultant field, so that it cannot deliver torque.

The frequency in the stator is the same as that applied to the commutator brushes. The frequency in the rotor is proportional to the number of poles and the speed of rotation, plus the frequency applied to the commutator. The field necessary to produce torque in the motor can be supplied to either member if the correct frequency is used at all times.

For stator excitation, the frequency is low and passes through zero as the main motor passes through synchronous speed. For rotor excitation, the available frequency is line frequency and to make the rotor frequency the same, the number of poles and speed of rotation must agree with line frequency at all times. This means direct connection or some special electrical connection, as will be shown later.

In Fig. 5 a stator-excited commutator motor is shown which returns its power to the line through either a synchronous or an induction generator. The main set consists of a synchronous generator and an induction motor of full capacity, with a small frequency converter on the end of the shaft. This is only of exciter capacity for the commutator machine, and has the same number of poles as the main induction motor.

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The auxiliary set consists of the commutator motor and the generator of the same capacity.

The voltage applied to the small frequency converter consists of a constant part with a small additional part varying with the load, which gives a compounding action (not shown). The voltage on the commutator is fixed, and various voltages may be taken off by changing the relative position of the brushes. The commutator of the frequency changer

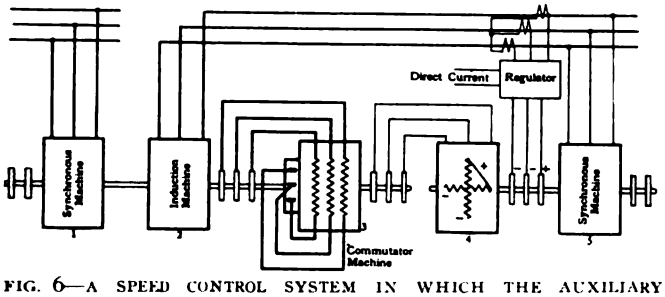


FIG. 6—A SPEED CONTROL SYSTEM IN WHICH THE AUXILIARY COMMUTATOR MACHINE IS EXCITED ON ITS OWN ROTOR
The machine illustrated in Fig. 1 is of this type.

has two brush yokes which are rotated in opposite directions. The exciting winding of the commutator motor is connected between brush yokes, so that the voltage applied can be varied from a maximum value in one direction, through zero, to a maximum value in the opposite direction by shifting the brushholders on the two yokes, to which the windings are connected, past each other.

Power-factor can be improved by special movement of the brush yokes and the addition of an exciting winding to the commutator machine. The load regulator acts through a pilot motor on the brush-yoke mechanism.

In Fig. 6 the commutator machine 3 is excited from the rotor through collector rings tapped into the rotor winding. The commutator machine is on the same shaft as the main synchronous (1) and induction (2) machines and has the same number of poles as the induction machine. The excitation of the commutator motor may be supplied by any variable voltage means at line frequency. A small synchronous-synchronous motor-generator (4, 5) set is shown which provides easy control and fine adjustment. The load regulator acts on the field rheostat in this case. Power-factor control is obtained by providing a double exciting winding on the exciter—one for speed control, the other at 90 electrical degrees for power-factor control.

In order to avoid the limitations on the commutator motor due to its being on the same shaft as the main motor, thus requiring the same number of poles, the commutator machine can be put on a separate set by using the connection shown in Fig. 7. This adds two machines of exciter capacity and the usual induction generator to return the power to the line.

The main set consists of the synchronous machine 1, the induction machine 2, and a small induction machine 3 of exciter capacity. The auxiliary set consists of the asynchronous machine 5, the commutator machine 4 and a smaller commutator machine of exciter capacity 6.

To obtain the correct frequency for exciting the commutator motor 4, the exciting current is taken through two machines 3 and 6, one on each of the two shafts in order to get the effects of the slip in each of the induction machines 2 and 5. Machine 3 has the same number of poles as 2, while machine 6 has the same number of poles as 4 and 5. The line frequency obtained through transformers or a synchronous-synchronous motor generator set is applied to the collector rings of machine 6 and is converted on the commutator of machine 6 to a frequency proportional to the slip of machine 5 i.e., $s_1$. This frequency is applied to the stator of machine 3 so that the field set up by it rotates in the same direction as the rotor. The frequency which then appears at the collector rings is equal to the speed of rotation $(1—s)$ minus the slip frequency $s_1$ or $1— s — s_1$. This frequency is applied to the collector rings of the main commutator motor 4. The speed of rotation of 4 i.e., $1—s_1$, is subtracted from the frequency $1— s —s_1$ applied to its collector rings, so that the frequency induced in the stator of 4 is $(1 — s — s_1) — (1 — s_1)$ or $—s$. This is the same frequency that is available from the rotor of the main machine 2 except for the minus sign, which is taken care of by reversing the connections between machines 2 and 4.

The auxiliary commutator machines in the sets of Figs. 5, 6 and 7 are built with compensating windings on the stator which, as usual, are connected in series with the brushes and rotor winding. The field set up by this winding in practical machines

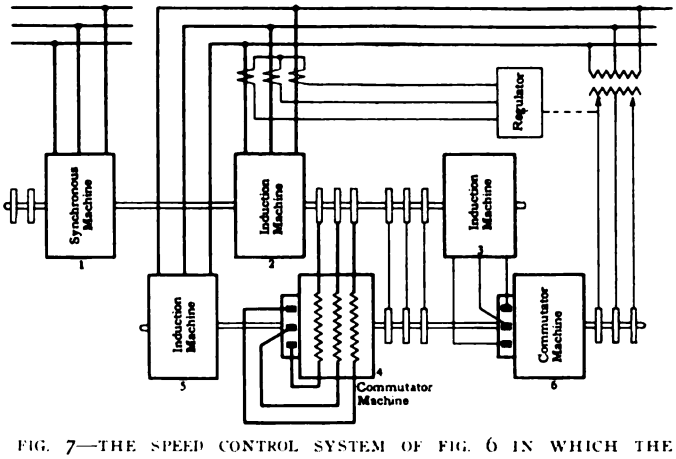


FIG. 7—THE SPEED CONTROL SYSTEM OF FIG. 6 IN WHICH THE COMMUTATOR MACHINE IS ON A SEPARATE SHAFT
The regulator mechanically shifts the taps on the transformer.

exactly, or almost exactly, neutralizes the field set up by the commutator currents. The resultant field is practically zero and so no torque can be produced by the motor. Another field is necessary before the armature current can produce any torque. This field can be supplied either to the stator or rotor if the correct frequency is used. It may be supplied to a

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separate winding or it can be superimposed on a winding already there for other purposes.

In Fig. 5, the field is supplied to a separate winding on the stator at slip frequency, which at all times has the same value as the main motor. The speed of the outfit is changed by varying the field strength and consequently its voltage. If the speed of the main motor is sufficiently far from synchronism that the rotor frequency is high enough to operate through a transformer, this slip frequency can be used to excite the stator. At speeds near synchronism, the rotor frequency is so nearly direct current that the transformer does not develop any voltage on the secondary side. To overcome this difficulty for operation from speeds slightly below to slightly above synchronism, another machine of the frequency converter type is connected in series with the secondary transformer. This machine is of exciter capacity; is similar to a synchronous converter armature with only a magnetic ring around it instead of poles and frame; is mounted on the main motor shaft; has the same number of poles as the main motor.

The collector rings are supplied at line frequency. Variable voltage on the commutator may be obtained by supplying variable voltage to the collector rings by transformer taps or other means, or constant voltage may be applied to the collector rings and the variable voltage obtained by varying the distance between brushholders on the commutator.

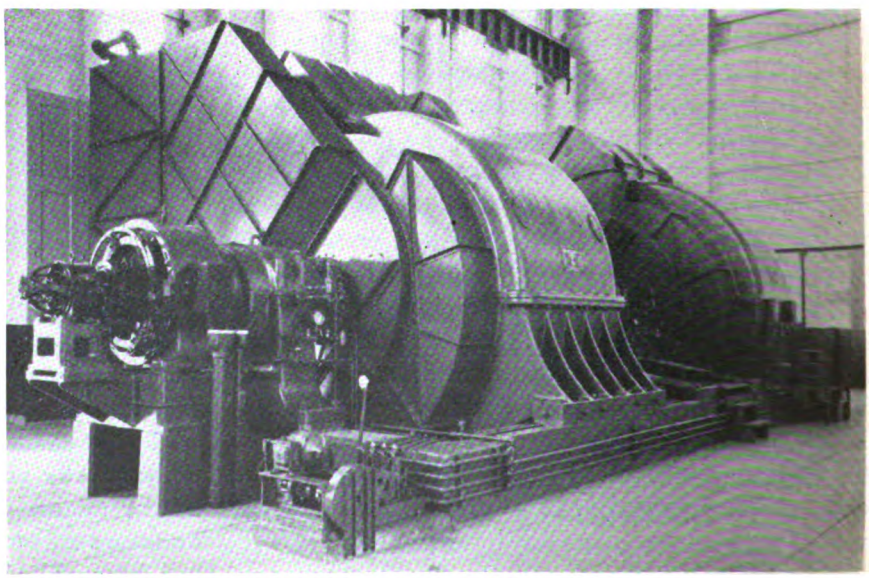
The type of exciting winding depends on the mechanical construction of the stator, which is determined by the means used to obtain good commutation. If poles are used, the poles and commutating poles are proportioned as in a direct-current motor, and the exciting winding will be similar to shunt coils on a direct-current machine. If commutating poles are not used, the stator is similar to an induction motor stator and the exciting winding will be a distributed winding. The commutation of the machine is accomplished through avoiding all causes for higher harmonics, such as notches, etc., with some help from resistance leads between coils and commutator.

In all stator-excited commutator machines, the exciting frequency goes from one value through zero up to another value. As the frequency passes through zero, the reactance in the circuits vanishes and there is only an ohmic drop. As the frequency increases, the reactive drop increases and the resultant voltage changes in angle. This change in angle near synchronism has to be taken care of by special connections in the exciter circuit near synchronism, or by some other equivalent means.

In Figs. 6 and 7, the excitation is supplied to the rotor windings of the commutator motor through taps and collector rings, as in a synchronous converter. No special exciter winding is necessary. The exciter frequency is always nearly normal line frequency, so that the reactance in the exciter circuit does not go through zero. The control is simple, as it is all on the rheostats in the field of the exciter and only handles direct-current exciter currents.

# A New 30 000 Kv-a Frequency Changer

This frequency converter set of the Southern California Edison Company converts 30 000 kv-a from 50 to 60 cycles. The set runs at 600 r.p.m. and is the largest frequency changer set yet built for that speed. The small direct-current generator at the extreme left end is the pilot exciter for the high-speed excitation system. This generator provides excitation for the main exciter which is immediately to the right. The main exciter in turn excites the 50 cycle motor. The 60 cycle generator with its single exciter, which cannot be seen in this picture is on the right end. The four main bearings are supplied with oil under high pressure from the pumping set in the foreground. The huge cooling air ducts from the side of the building to the machines, provide the necessary ventilation.



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# Vertical Transportation

## A Summary of the Present Elevator Situation

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THE electric elevator has displaced the various types of hydraulic machines because electric drive has many advantages, one of the most important being that it consumes power only in proportion to the load in the car. The motor required is small because of the use of counter balances equal to the weight of the car plus 40 percent of the maximum load in the car, so that the load lifted by the motor is only 60 percent of the live load. If the car descends light the motor does work in lifting the counterweight. Part of the time the load is overhauling and the motor returns power to the line. The hydraulic machine takes the same amount of water for a trip without reference to the load in the car and therefore consumes much more power than the electric elevator.

THE NEW 40-STORY GRANT BUILDING, PITTSBURGH, TO BE EQUIPPED WITH TWELVE INDUCTOR-CONTROLLED ELEVATORS

The time required to accelerate a hydraulic elevator is directly proportionate to the load, as the power available for accelerating the load is a function of the hydraulic pressure which is constant. The electric elevator does not have this limitation as its motor can deliver excess torque during the accelerating period. Its time of acceleration depends only on the power supply, if the elevator motor is large enough for the duty cycle. The smaller the stored energy of the motor armature the less the power required for a quick acceleration or stop. The direct-current motor has a distinct advantage over the alternating-current motor on account of its smaller armature diameter.

The first electric elevators were of the drum type. The motor rotated the drum through worm gearing. The speed regulation of the motors was poor as armature series resistance was the only method of control. Some motors were compound wound; the controller short-circuiting the compound winding at the end of the accelerating period. At first the car was controlled by a hand rope and a little later by a lever or handwheel in the car. These control devices were adapted from the existing control for hydraulic machines and operated the motor controller manually. The car switch or pushbutton control was a later development.

The first major improvement was the use of an adjustable speed motor, having shunt field control, and the addition of a resistor in shunt with the armature to obtain the slow speed required for accurate landing.

The winding of the ropes on the drum introduced many mechanical limitations in the design of these machines so that a distinct improvement was made when a traction sheave was substituted for the drum. A further improvement consisted in building a motor operating at about 60 r.p.m. and placing the traction sheave on the motor shaft. This was known as the gearless traction machine.

UNTIL 1916 the standard control was of the ordinary rheostatic type. Current peaks were kept small by using a large number of accelerating steps requiring careful adjustment and continual inspection. About this time another improvement was made by introducing a reactance coil in the armature circuit which materially reduced the current peaks. Thus smoother operation was obtained with fewer accelerating steps.

The use of a traction machine added materially to the safety of the electric elevator as it prevented overtravel due to the loss of tractive effort if either the car or counterweight rested on the bottom of the hatchway. When the tractive effort is lost there can be no further movement of either the car or counterweight. The oil buffer, developed to stop the car or counterweight at the bottom of their travel, is also an improvement over the springs previously used for this purpose.

Ten years ago elevator development became very active due to increased competition in the gearless traction field. Two-speed alternating-current motors were also applied to high-speed geared elevators and provided with speed ratios of 4:1 and 6:1. Automatic

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leveling which had been developed for freight elevators was being introduced for passenger cars. At this time the leveling was obtained by means of an auxiliary drive attached to the main machine.

A NEED for better control of the car at slow speeds led to the development of other control systems to replace the rheostatic type. Multi-voltage was first tried with a special motor-generator set to furnish different voltages to the elevator motors. This gave a fixed speed to the elevator car corresponding to each voltage, but in stepping from one voltage to the other, particularly from a higher to a lower voltage, it is necessary to insert resistance in the circuit and carefully control this resistance to prevent jerky operation of the elevators.

During 1922 variable-voltage control, which had been tried with limited success about 20 years before, was developed and has since superseded other methods of control for high-class elevator installations. This system makes use of a separate generator for each elevator motor. The speed and direction of travel of the elevator is controlled by changing the field of the generator. This control system gives such good speed regulation at slow speeds that automatic leveling can be obtained with the main motor, thus eliminating the auxiliary drive previously used.

Variable-voltage control is particularly adapted for operating elevators from alternating-current network distribution systems. These systems are rapidly being extended in our large cities replacing the direct-current systems and the older methods of alternating-current distribution. In these networks the same system supplies both power and light, and therefore any abrupt demand for considerable power affects the lights over the adjacent area. For this reason it is necessary either to limit the maximum current peaks; or to reach these peaks in reasonably small steps. When two-speed induction motors are used for operating elevators, the maximum power is taken at starting. This power is often at a low power-factor. With the variable-voltage system, the starting load on the motor-generator set is automatically limited to a low value. When the elevator is started the voltage of the generator is low and, therefore, the power taken from the network is less than full load, although the elevator motor itself requires more than full-load current. As the elevator accelerates the current increases and then returns to the amount required to operate the elevator at full speed.

IF the car overtravels in making a landing, time is lost in running by and returning to the level even though the leveling is obtained automatically. To avoid this delay and the disagreeable sensation due to reversing the car motion, automatic landing was developed, which stops the car at the landing without over-traveling. Automatic leveling required the operator to stop the car within a few inches of the landing by means of the car switch. Automatic landing takes care of the slow down as well as the stopping of the car. The operator simply places his switch in the off position and the automatic control initiates the slow down at the proper time to stop the car level with the landing. This reduces the time of stopping over manual slow down as it permits operating the car at full speed until it is closer to the landing. When automatic landing came into general use, it was found that the cam-operated slow-down switches in the hatchway were objectionable due to the impact of the cam at high speeds. A study of this question resulted in developing a magnetic "inductor switch" mounted on the car which is operated by iron inductors, so located in the hatchway as to affect a magnet mounted on the car. When the car magnet is energized, on passing an inductor, the magnet armature of the inductor closes and operates the switch. No mechanical contact is made and, therefore, the switch is noiseless in operation and not subject to mechanical wear. This method of automatic stop is known as "inductor landing."

Light sensitive relays have also been tried for this purpose. A beam of light located in the hatchway passes through a slit at the proper level and operates a light sensitive relay located on the car. The light source is energized by push button control when it is desired to make a stop.

AUTOMATIC inductor control may be used to advantage with a variety of signal systems. Where the service is intermittent, as in hotels and small office buildings, the cars not run on regular schedules and a simple flash light annunciator is satisfactory. Where an annunciator only is used, the operator relies upon watching the hatchway to determine the point at which to center the car switch handle. When a bank of elevators are operated on a regular schedule, what is known as a car operator's signal system is used. The operator receives a light, sometimes accompanied by a bell, when he reaches the point at which the power should be turned off in order to stop at a floor. The position in which the operator's flash occurs is so synchronized that, when stopping from a signal, the operator need not pay attention to the position of his car in the hatchway.

The hall buttons can be arranged to stop the car automatically in the same manner as the ordinary push-button control used in residences. The car can also be provided with a set of floor buttons. This is an extension of the well known push-button control system to high-speed elevators. When this system is used, the operator initiates the starting of the car with the car switch and then returns the switch to the central position. The car continues to travel until it reaches the first floor for which a signal has been set, either by the hall button or the button in the car. After the car has stopped at the landing and taken on or discharged passengers, the operator again starts it with the car switch and immediately centers his handle. This permits

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the car to make the next registered stop. When this system is used, passengers are requested to announce their destination when entering the car, so that the operator can set up the proper floor stops on the floor buttons located in the car. This system eliminates the necessity of centering the car switch at the proper time to stop at a definite floor.

The development of this control introduced considerable complication and reduced the flexibility of operation that was obtained with the car switch and signals. The next development was, therefore, a simpler form of control known as "preregistered signals." The buttons in the car and landing are operated in the same way but the elevator operator keeps the car switch handle in the running position until the car signal flashes; he then centers his handle. The car continues to run at full speed until it reaches the first inductor switch, when it slows down and automatically stops at the floor corresponding to the button which was depressed. Practically all recent high-class installations are using one or other of these automatic systems.

TABLE I—VARIOUS METHODS FOR CAR SWITCH CONTROL

| | | |
|---|---|---|
| Car Switch Control With Operator | 1—Signals only | |
| | 2—Signals and automatic leveling | |
| | 3—Signals and automatic landing when car switch is centered to select floor | |
| | 4—Floor button control or signal control | Same as 3 except car switch is centered immediately after car is started. The signal system stops the car at the proper floor |
| | 5—Pre-registered signals and Automatic landing. Operator centers car switch when signal flashes | |
| | 6—Automatic dispatching can be added to any of the above combinations. | |
| | 7—Manual dispatching with control of car speeds can be added to any of these four combinations. | |

Automatic dispatching has been developed for a bank of elevators and is gradually coming into use. It may be arranged to signal the car operators direct or the dispatcher may transmit the signal, modifying it according to circumstances. The dispatcher can also be given control over the speed of the elevators where it is desirable to do so.

When automatic landing is used, it is logical to operate the hatchway doors and the car gate automatically, as this reduces the time required for handling passengers and reduces the physical effort required of the operators.

The various combinations of control are shown in Tables I and II. The multi-car system of pushbutton control with an "up" and "down" button at the landing saves considerable time for an active elevator. When inductor landing is used, pushbutton elevators can be run at as high a speed as car switch elevators, but usually the service conditions do not justify it.

EACH convenience added to the control tends to increase its cost and complication, but after a system has been thoroughly worked out much of the complication is eliminated and the details of the elevator control are simplified and improved. The signal circuits can now be made as rugged as the rest of the elevator system. Improvements in landing and dispatching make elevators safer and enable them to render better service in handling passenger traffic. These improvements make it possible to handle a larger number of people per elevator and add to the comfort of the passengers. The space occupied by an elevator represents floor area which is taken out of every floor served by that elevator. This reduces the revenue space in a building. If the improvements in the operation of elevators enable a building to give satisfactory service with two less elevators, we can assume that the space on each floor which would have been occupied by these elevators will be available for renting is equivalent to at least 50 square feet per elevator or a total of 100 square feet. If the building has twenty floors this will represent a saving of 2000 square feet which might be rented for $2.00 to $4.00 per square foot, or from $4 000 to $8 000 per year.

TABLE II—VARIOUS SYSTEMS FOR PUSHBUTTON CONTROL

| | | | |
|---|---|---|---|
| Push Button Control No Operator | One car | 1—Single call—Oldest and simplest type | |
| | | 2—Multi-call | Single Button<br>Up and Down Button |
| | | 3—Inductor landing or leveling with either 1 or 2 | |
| | Two or more cars | 1—Two button multi call | Inductor landing or leveling<br>Floor signals are desirable for more than two cars |
| | | 2—Two car automatic sequence | Same as 1 with automatic sequence control. Up car answers up signals and down car, down signals—operation reversed at ends of travel—cars remain at ends of travel until called. |
| | | 3—Three or more cars with automatic dispatching | Same as 2, with automatic dispatching added. This keeps the cars moving at regular intervals. |
| | Dual Operation | 1—Push button or car switch control with means for selecting one of the other method by means of a change switch. | |

The two elevators omitted would probably have cost at least as much as the additional expense for equipping the remaining elevators with automatic control. Figures based on general assumptions may be misleading because each building should be studied itself. In some cases all floor space cannot be made revenue producing even if part of the elevators are omitted. On the other hand, sometimes the improved elevator service obtained by automatic control will permit the owner to get increased rental for his space. The time required to travel from the ground floor to the upper floors is an important item, especially at the rush times of the day when a large percentage of the tenants of the building are coming in or out. The comfort and convenience of the passengers is also an important item. The cost of elevators does not represent a large percentage of the total building cost but they are a most important factor in making the building a success.

There is no doubt that we shall see further improvements in the electric elevator in the next few years as the problem of "vertical transportation" is being studied carefully by several large and capable groups of engineers.

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# Bimetal: The Temperature Sentinel

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BIMETAL constitutes the "brains" of certain devices which are more reliable in doing their duty than human hands. Placed in an electric oven a bimetal strip can be made to cut off the heat when the temperature becomes too high and turn on the heat when the temperature is too low. For the same purpose bimetal is used in thermostats to control the temperature in houses, electric flat irons, electric furnaces, gas and electric stoves and other devices where action is required at some set temperature to open or close a circuit or valve.

A bimetal strip may be made to stand guard beside an electric motor to protect it from injury from overload. If an overload should occur, the bimetal will act so as to interrupt the power to the motor and prevent a dangerous temperature condition. Motors, like men, can and are sometimes required to withstand overwork for a time. The time, of course, depends on the intensity of the overwork; that is, the greater the intensity of overwork the shorter the time during which the work should continue. In the case of the motor, the bimetal takes this into consideration by allowing the motor to carry only the load for which it is designed.

Bimetal, as the name implies, refers to material which is composed of two metals. Often it is called "thermostatic metal" because it was first used as the temperature-sensitive element of devices for controlling and regulating temperature. Bimetal has for some time been a commercial product. In the last few years much progress has been made in its manufacture and its application has been widened to include many kinds of devices where a temperature responsive element is desired. Fundamentally, bimetal is used to give a mechanical motion in response to a change in temperature. In other words, heat is transformed into mechanical energy which in this case is accomplished in a cheap, simple and efficient manner. Of course, only a small amount of energy, of the order of an inch-pound, is involved.

Equal thicknesses of two dissimilar metals are rolled and bonded together while at a high temperature. The result is a two layer material which is further rolled to the desired thickness. The layers are so intimately joined or bonded that only a close inspection of the joined edges will reveal the dividing line between the two metals. The alloys constituting the two layers of a bimetal must have different coefficients of expansion. The greater this difference the more responsive the bimetal is to changes in temperature, if other things remain unchanged. Theoretically there may be as many kinds of bimetal as there are combinations of two metals. However, only a few of these combinations are useful, because of certain characteristics a bimetal must have. It must be possible, commercially, to roll and bond the two metals together; the component parts must have a fairly high strength at normal and at a higher operating temperature; and the bimetal itself must be responsive to temperature changes. One bimetal, composed of brass and a nickel-steel alloy, has a maximum operating temperature of 150 degrees C. This bimetal is suitable also where maximum response per degree is required; where the load to be carried is light; where the heat supply is low; and where quick cooling is desirable, made possible by the high heat conductivity of the brass component. Another bimetal, composed of alloys of copper-nickel and nickel-steel, has a maximum operating temperature of 300 degrees C. This bimetal does not give as great response per degree change of temperature as the one above, but is stronger and will stand higher internal stresses and therefore higher temperatures and external loading. A selection from these two bimetals may be made on the basis of temperature, heat conductivity, strength and response per degree change in temperature.

In the following discussion the illustrations used are exaggerated in order to show the action which takes place. Fig. 1 shows two strips of the same dimensions at an initial temperature, made from two materials which have different coefficients of expansion. In Fig. 2 these strips have been heated above the initial temperature; *a*, the metal with the lower coefficient of expansion has become longer, but has been exceeded in length by *b*, which has a higher coefficient of expansion.

Suppose the strips, Fig. 1, are now bonded together into a bimetal strip, placed in clamps to prevent bending and heated above the initial temperature. They will appear as in Fig. 3. The two components, now held to one common length, have a mutual effect on each other; *a* is stretched beyond its normal heated length and *b* is compressed to less than its normal heated length. In the stress diagram the distribution of internal stresses is shown; compression on the left and tension on the right. Since the strip is not allowed to bend, the stresses will be uniformly distributed and the total force acting on each component will be the same, therefore, the stresses will be the same. It is easily seen that there will be tension in *a* and compression in *b* as shown in the stress diagram. In this stress diagram and those which follow, with the exception of Fig. 8, the

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stress conditions shown apply to all cross-sections of the strip throughout its length. If the clamps are removed with the temperature unchanged, the strip will appear as in Fig. 4. Here the stresses in certain regions are relieved since the strip is allowed to assume its free heated shape. Stresses along the

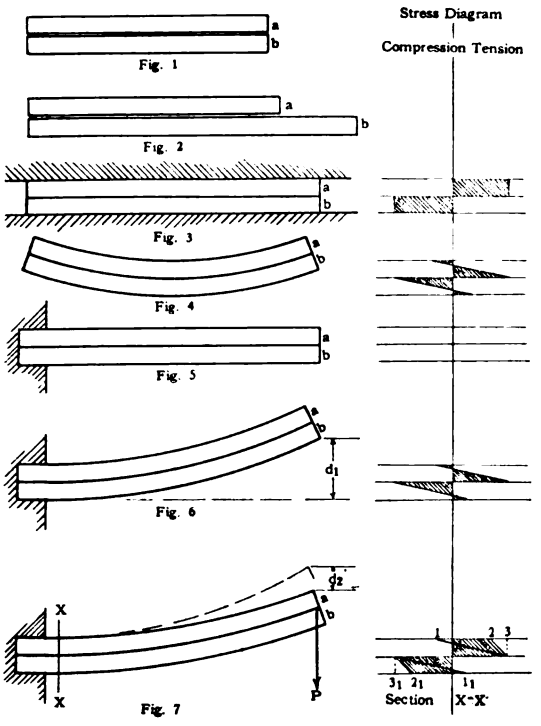


FIG. 1—AN UNBONDED BIMETAL STRIP
FIG. 2—AN UNBONDED BIMETAL STRIP, HEATED
FIG. 3—A HEATED BIMETAL STRIP, BENDING PREVENTED
FIG. 4—A HEATED BIMETAL STRIP, BENDING PERMITTED
FIG. 5—A BIMETAL STRIP AS A CANTILEVER BEAM, COLD
FIG. 6—A BIMETAL STRIP AS A CANTILEVER BEAM, HEATED
FIG. 7—A BIMETAL STRIP AS A CANTILEVER BEAM, HEATED, LOAD APPLIED AT THE FREE END

bonded surface are not changed. However, the stresses decrease with increased distance from the middle and at the extreme outer surface they are reversed due to the bending action. In other words, when the strip is heated free, it will bend with a uniform curvature. The stresses in *a* are a maximum in tension along the inner surface and have a low compression value along the outer surface with a gradual change from one to the other in the regions between. The stresses in *b* are maximum in compression along the inner surface and have a low tension value along the outer surface, with the same distribution as in *a*. When the strip cools it will become straight and the internal stresses will disappear.

Let us consider one way in which the action of a bimetal strip may be used to produce practical results. If the strip is fastened at one end, the other end will move in response to a temperature change. The free end may have an electrical contact mounted on it or be connected so as to move a load and perform work. Such a strip is shown in Fig. 5. After the temperature has been raised the strip will appear as in Fig. 6. The corresponding stress diagram is the same as for Fig. 4. The end of the strip will deflect an amount $d_1$ with respect to the fixed end. If now a load $P$ is applied to the end of the strip, as in Fig. 7, some of the deflection $d_1$ will be annulled by an amount $d_2$. The stresses remain unchanged along the neutral axis, are increased in tension on the top and in compression on the bottom. In the diagrams, the moduli of elasticity are assumed to be the same, which results in the neutral axis remaining at the center of the strip when external loading is applied. Practically the moduli are not always the same. However it can be shown that a considerable difference in the moduli must exist to cause an appreciable shift of the neutral axis from the geometric center or bonded surface. In calculations where the strip is considered as homogenous material $E = \frac{1}{2}(E_1 + E_2)$ is a close approximation to actual conditions. In a loaded cantilever the stresses are a maximum near the fixed end. Section $XX$ of the stress diagram in Fig. 7 shows the distribution due to a combination of thermal and load stresses near the fixed end of the strip. As the load $P$ is increased, the stress in the outer regions will change from 1-2 to 3 in *a* and from $1_1$-$2_1$ to $3_1$ in *b*. When the curvature due to heat is just annulled; i.e. the strip is flattened by the load $P$ in the section $XX$. the condition is then the same as exists in Fig. 3; i.e., the stresses are uniform over the cross-section. If the load is greater than necessary to produce this condition, the stresses in the outer regions will be greater than the maximum thermal stresses of Fig. 6. It can be shown mathematically that $d_2$, the deflection due to a load $P$, may increase to approximately two-thirds of $d_1$ without increasing the internal stresses beyond the thermal stresses.* In other words, if the load deflection $d_2 = 2/3$ the heat deflection $d_1$ the section $XX$ will have zero curvature, and the stresses in this section will be uniform as in Fig. 3.

The component metals tend to expand in all directions, especially along and across the strip. There results lengthwise and crosswise curvature

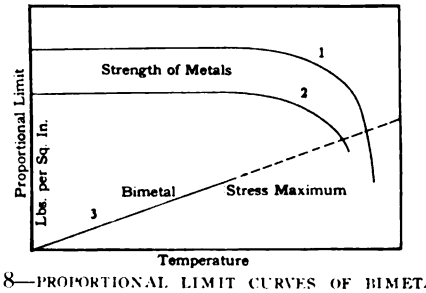


FIG. 8—PROPORTIONAL LIMIT CURVES OF BIMETALS

which causes the bimetal to assume a spherical shape. Curvature across the strip produces a channel shape which stiffens it and checks to some extent the lengthwise curvature. The cross curvature effect is practically negligible if the width of the strip is held within limits. In order to prevent any crosswise curvature effect, the bimetal width should be

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not more than approximately twenty times the thickness of the strip.

In the practical application of bimetal it is presupposed that the bimetal will maintain its calibration and repeat its functions faithfully. When in continuous operation this condition is met when the bimetal is properly applied. It is important to note the cause and effect of failure to meet this condition which might occur if the bimetal is wrongly applied or abused when in use. Injury or failure of bimetal can usually be traced to a condition where a temperature in excess of the maximum operating temperature has existed. Curves 1 and 2 in Fig. 8 show the manner in which the proportional limits of the component metals change with temperature, the upper curve being for the stronger metal, which may be either the high or the low expansion metal. The maximum stress in bimetal due to temperature, also shown in curve 3, Fig. 8, is independent of the dimensions of the strip and is proportional to the temperature. If the temperature is raised to a point where the maximum heating stress approaches the proportional limit of the weaker material, the bimetal will fatigue rapidly or fail and assume a permanent bend. When for example the low expansion component of a bimetal has its proportional limit exceeded due to overheating, the failure will be in tension producing permanent elongation. This component will regain its strength on cooling and, having a longer effective length, will cause the bimetal to assume a permanent bend in the direction opposite to that produced by heat. By the same reasoning it can be shown that if the high expansion side is weaker the permanent bend will also be in the direction opposite to that produced by heat. The two metals will not necessarily have the same proportional limits, which means that maximum operating temperature must be based on the weaker material. Conditions which produce stresses just within the proportional limit will only delay failure of the metal until a number of operations have been performed. Therefore, the bimetal temperature should be kept within the recommended limits.

Referring to Fig. 4, it is important to note that in cases where failure does occur, only the inner layers which are subjected to high stresses are affected. This makes detection of such failure more difficult and perhaps impossible except after a great number of operations. In actual tests to determine endurance, the bimetal is clamped as in Fig. 3 so that the same stress will exist throughout the metal section. In this case, failure or fatigue will show itself readily when the operating temperature has been exceeded.

The action of a bimetal strip when allowed to bend freely is expressed in the following formula in terms of the physical properties and dimensions of the strip:—

Where, coefficients of expansion = $\alpha_a$, $\alpha_b$
Moduli of elasticity = $E_a$, $E_b$, $E_a/E_b = n$
Thickness of the strip (inches) = $H$
Temperature change (degrees C) = $T$
Radius curvature of strip (inches) = $R$

$$1/R = \frac{24}{14 + n + 1/n} \frac{(\alpha_b - \alpha_a)\, T}{H}$$ *

As in the above discussion we are interested in the deflection of one end with respect to the other, rather than the radius of curvature. Let $L$ be the length of the strip and $d_1$ (Fig. 6) the deflection of the end. Then $d_1 = L^2/2R$ when the curvature is small, as is generally the case.

Therefore:—

$$d_1 = \frac{12}{14 + n + 1/n} \frac{(\alpha_b - \alpha_a)\, TL^2}{H}$$

It may be noted here that the deflection $d_1$ is proportional to the temperature change $T$, the difference between the coefficients of expansion, the square of length $L$ and inversely proportional to the thickness of the strip $H$. The bending depends on the ratio of the moduli of elasticity and is the same regardless of which is the larger, so long as they give the same ratio. The ratio of the moduli $n$ must change considerably before an appreciable change occurs in the deflection $d_1$.

An external load $P$ applied to the end of the strip, Fig. 7, will cause a deflection $d_2$ which can be expressed by the usual cantilever formula:—

$$d_2 = \frac{PL^3}{3EI} \qquad I = \frac{H^3W}{12} \qquad E = \frac{E_a + E_b}{2}$$ *

where $W$ = width of the strip.

then, $d_2 = \frac{4\, PL^3}{EWH^3}$

The load deflection will annul part of the heat deflection, so the actual deflection $D$ under load will be expressed by:—

$$D = d_1 - d_2$$

$$D = \frac{12}{14 + n + 1/n} \times \frac{(\alpha_b - \alpha_a)\, TL^2}{H} - \frac{4\, PL^3}{EWH^3}$$

From this expression the effect of each factor on the deflection of a loaded bimetal strip can be observed. For example, for a given temperature the deflection $d_1$ is increased by decreasing the thickness $H$. However this will also increase the deflection $d_2$ at a greater rate, due to the load. The same would apply to an increase in length $L$.

The width of the strip $W$ has no influence on the heat deflection, and may be varied to control the deflection due to external load. Theoretically two-thirds of $d_1$ may be annulled by the load deflection $d_2$ without increasing the thermal stresses. Practically, the load deflection should be small in relation to the heat deflection. The maximum stress due to heating is given by the formula:—

$$P = \frac{E}{2} (\alpha_b - \alpha_a)\, T$$ *

Where $P$ represents tension in $a$ and compression in $b$ (Fig. 4). It is shown here that the maxi-

*S. Timoshenko; *Journal of the Optical Society of America and Review of Scientific Instruments*. Vol. II, July-Dec. 1925.

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mum stress is independent of the thickness of the strip. Considering $E$, $\alpha_a$ and $\alpha_b$ as constants of the materials, the stress is proportional to the temperature change $T$.

*Example*:—Given a strip of bimetal made from material of known constants, the strip to be considered as a cantilever beam, with temperature and external load, find the deflection at the end of the strip. The bimetal is composed of a low expansion nickel-steel alloy and a high expansion copper-nickel alloy.

$E_a = 27 \times 10^6$ $T = 150°C.$
$E_b = 22 \times 10^6$ $P = 0.3$ pounds
$\alpha_a = 5 \times 10^{-6}$ $H = 0.03$ inches
$\alpha_b = 13 \times 10^{-6}$ $L = 3$ inches
$n = \frac{E_b}{E_a} = 1.23$ $W = 0.5$ inches
$\frac{E_a + E_b}{2} = 24.5 \times 10^6$

$$D = \frac{12}{14 + 1.23 + \frac{1}{1.23}} \times \frac{8 \times 150 \times 9 \times 10^{-6}}{0.03} - \frac{4 \times 0.3 \times 27}{24.5 \times 5.0 \times 27}$$

$D = 0.27 - 0.10 = 0.17$ inches

# A Theory of Lightning

## II--Protection of Lines against Lightning

CHAS. LeG. FORTESCUE

WHERE lines are subject to frequent and severe lightning the matter of stability becomes of increasing importance. The subject of stability has been fully treated and discussed in the past four years. As a means for studying the stability of systems, oscillographic power-surge records, with initiating devices, have been developed so they are brought into operation at the initiation of the fault and record all the data. A public utility equipped with such devices may analyze the data and decide what parts of their system are inadequately protected; in other words, the first precaution against the effects of lightning is to stabilize thoroughly the transmission system. Of course, the more thoroughly lines can be protected against lightning disturbances, the closer to the stability limit they can be worked during normal steady conditions and therefore the more economically they can be operated.

### INFLUENCE OF TOPOGRAPHY ON LINE CONSTRUCTION

Generally speaking, lightning gradients are higher at the high points of the earth's contour, though this may be influenced by meterological conditions which determine the general path of thunderstorms. As a rule, however, the lower the lines the less the susceptibility to lightning. Thus some advantage can be obtained by keeping the lines as near the earth as possible. Perhaps this is the reason why wood pole lines have appeared to be less affected by lightning than steel tower lines.

### GROUND WIRES FOR PROTECTION OF LINES AGAINST LIGHTNING

For obvious reasons the line cannot be brought very close to earth; therefore, some method of bringing an artificial earth close to the wires may prove effective in providing lightning protection. The ground wire is such a device. Ideal protection would obviously be obtained if the ground wires could completely surround the conductor and could be close enough to the conductor to be considered practically coincident therewith. This ideal cannot be realized and even if it could it probably would not be economically justified.

A single ground wire gives a certain amount of protection. With a 220 kv transmission line with horizontal spacing, a single ground wire placed in the most favorable position and as close to the transmission line conductors as feasible, considering all the necessary requirements, will reduce the surge potentials by about 25 percent. With the same transmission system, two ground wires, properly located and as close to the transmission conductors as is feasible, will make a reduction of approximately 40 percent of the surge potentials. Going one step further, three ground wires properly located and arranged, will cause a reduction of about 50 percent. Obviously, two ground wires will cost more than one ground wire and three ground wires will cost more than either. Therefore we encounter an economic problem which requires us to decide how many ground wires are economically justifiable.

Consider a 14 unit string of insulators which has a 60 cycle dry flash-over of about 700 kv r.m.s. or 1000 kv crest value. Suppose it is desired to protect the line against all surges below a crest value of 2000 kv maximum. One ground wire will reduce the surge to a value of 1500 kv and therefore will be inadequate; two ground wires will reduce the value to 1200 kv which is still inadequate, whereas three ground wires will reduce the value to 1000 kv which may be sufficient to protect the insulator string from flashing over.

If two wires are used instead of three then it is necessary to increase the insulation of the line about 50 percent which would require at least 21 insulators in a string. This illustrates a rather extreme example, as it is unlikely that induced surges of 2500 kv crest will be caused frequently enough to require the protection of three ground wires. Two ground wires will protect against induced surges having a crest value of 1650 kv.

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The percent reduction in surge potentials for various arrangements of ground wires on 220 kv lines shown in Fig. 3 are given in Table I. The problem of ground wires is a purely geometrical one and depends upon the relative location of the ground wire with respect to the transmission wires and their images in the earth plane. Values that are more optimistic have been published in one laboratory, the optimistic results being ascribed to corona formation. These values based on the coefficients of capacity and induction, are the optimum figures that can be obtained, ignoring the effect of corona. The effect of high resistance grounds and the resistivity of the ground wires, etc., will reduce these values somewhat.

In addition to reducing the surge potential induced by the lightning stroke, ground wires offer further protective value by increasing the attenuation of the traveling wave which results from the lightning stroke. This is brought about by the fact that the ground wire with the earth, though of lower impedance than the earth alone, causes more energy loss in the traveling wave.

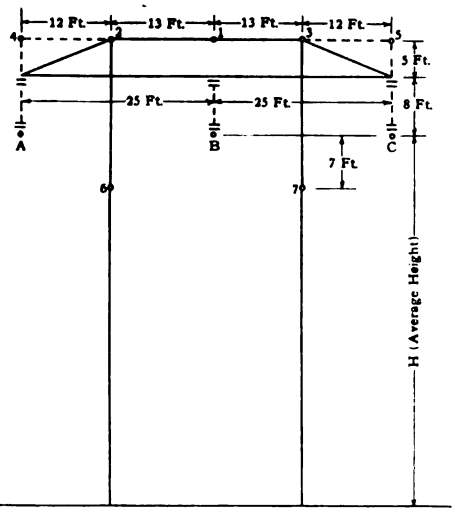


FIG. 3—CONDUCTOR AND GROUND WIRE SPACING ON A TRANSMISSION LINE TOWER

The currents set up in the earth and ground wire have high losses and thereby dissipate the energy of the surge.

It is recommended that conductors for ground wires have one layer of good conducting material such as copper or aluminum. Galvanized steel wire does not form a suitable conductor for this purpose. It is further recommended that such wires shall be flexibly supported and the same construction standards be maintained the way as for the line conductors.

In this discussion, the crest value of the surge has been emphasized. There has been considerable rather loose discussion on the use of insulators and the practical significance of the impulse factor of insulators. Impulse factors of the value of 1.4 or 1.8 have been cited and the impression given out that this high impulse factor is a protection against flashover from lightning surges. The time required for these surges to reach their crest value is probably a matter of five microseconds or more, and since a string of insulators will flash over in a fraction of a microsecond, the actual impulse factors for such a string of insulators at the full crest value of the surge will be nearer unity than 1.4 or 1.8. This matter will be more fully discussed later.

The impulse factor of strings of insulators has been emphasized not because of its connection with line protection but on account of its effect on the protection of apparatus against high voltage surges which flash over the insulators, a portion of which surges pass into the station apparatus. It is important to know what the impulse flashover of the insulator is in order to design the substation apparatus to withstand such impulses. In other words, if the insulator string has a 60 cycle crest flashover value of 1000 kv and an impulse ratio of 1.4 to a lightning wave of a certain steepness, the wave that will reach the apparatus will be one having a crest value of 1400 kv, but with the characteristic of a chopped wave and consequently of very short duration.

## OTHER REMEDIAL MEASURES

If it were possible to by-pass the lightning voltage surge to ground, without the power arc following the by-pass, we would have a very satisfactory method of getting rid of the surge. It has been proposed from time to time to place lightning arresters at intervals along the line, thereby providing a by-pass for the lightning surge to ground. This would be an ideal remedy if lightning arresters could be placed frequently enough to protect the line absolutely. But, in case an insulator string should flash over, the lightning arrester would not prevent the power arc from following because the arc potential of the insulator string is very much less than the counter-potential of the lightning arrester. If the economics of the situation could justify the placing of a lightning arrester at every tower, the problem would be solved.

A remedial measure proposed by Mr. Stewart* consists of using a string of insulators having extra units, and providing the string with top and bottom arcing rings and intermediate arcing ring and shunting part of the insulator string with a fuse. With such a

TABLE I—REDUCTION OF INDUCED LIGHTNING VOLTAGES FOR VARIOUS GROUND WIRE ARRANGEMENTS ON 220 KV FLAT HORIZONTAL SPACED LINE

| Number of Conductors | Conductor Position in Fig. 3 | Diameter in Inches | Average Reduction Percent | Induced Crest Kv for 50 Kv per Ft. Closed Gradient |
|---|---|---|---|---|
| Line Conductors 37 Ft. above Ground | | | | |
| 0 | | 0 | 0 | 1850 |
| 1 | 1 | ½ | 21.9 | 1480 |
| 2 | 2,3 | ½ | 36.6 | 1170 |
| 2 | 2,3 | 1 | 39.3 | 1120 |
| 3 | 1,4,5 | ½ | 48.0 | 960 |
| 5 | 1,4,5,6,7 | ½ | 57.1 | 795 |
| Line Conductors 75 Ft. above Ground | | | | |
| 0 | | 0 | 0 | 3750 |
| 1 | 1 | ½ | 27.7 | 2710 |
| 2 | 2,3 | ½ | 45.7 | 2030 |
| 3 | 1,4,5 | ½ | 58.2 | 1570 |

*Of the Union Gas & Electric Co., Cincinnati, Ohio.

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device when the surge hits the string of insulators a flashover follows. The resulting current blows the fuse which prevents the power arc from continuing in the path of the lightning flashover. At the same time the additional insulation is introduced into the string. The operation is so fast that relays have no time to operate and the line is cleared and remains in operation immediately after the lightning stroke. This measure has much to recommend it, provided it can be carried out economically. This seems to depend upon the manufacturers being able to produce a fuse which is economical and is satisfactory from an operating standpoint.

It has been suggested that wood pole construction acts in a very similar manner to the remedial measure of Mr. Stewart, namely, that flashover occurs in the string but the conduction takes place through the wood, and its resistance is too high to enable the power arc to establish itself. Thus at the end of the impulse discharge the insulator string is cleared and no outage occurs. Too frequently the flashover of the string of insulators leads to rupturing of the wood pole by lightning and brings about an outage for mechanical reasons. This is more serious than the flashover of a string of insulators on a steel tower transmission line which, with proper relay setting, will only mean the cutting out, for a short period of time, of part of a transmission line. A considerable number of utility engineers, who have had experience with both steel tower lines and wood pole lines, favor steel tower construction with adequate insulators and ground wires.

Wood pole lines might be used to advantage if provided with ground wires of proper design. Such ground wires should be insulated from the wood pole and the ground connection should be carried down at a sufficient distance from the pole so as to preserve whatever insulating value the pole may have. With this type of construction it may be possible to use the above mentioned advantage of the wood pole, without so much risk of rupturing the pole by the lightning discharge.

### FLASHOVER AND ITS RELATION TO TRANSFORMER INSULATION

The mechanism of the flashover of sphere gaps has already been discussed. It was shown that there are three important stages in the phenomenon, namely:—

1—The initial stage of ionization by collision.

2—The secondary stage, characterized by thermonic emission.

3—The breakdown stage, where highly conducting streamers are formed.

The secondary stage is reached at the 60 cycle flashover value of the gaps. If a surge of a given steepness is applied to the sphere gaps, the actual value of flashover of the sphere gaps will depend upon the time for the streamers to move from sphere to sphere, so that the steepness of the surge above the cycle crest value of the spheres is the important element. The steeper the wave above this point, the higher will be the value at which the sphere gaps will flashover. By actual experiment it was found that with 75 cm spheres separated at 40 cm the time required from the inception of the streamer stage to the completion of the streamer stage, or formation of the arc, was of the order of 0.01 microsecond. On the assumption that the streamers are evolved from both spheres simultaneously, the average velocity of travel would be one-fifteenth of the velocity of light. Actually the streamer from high potential sphere starts first, and moves about two-thirds of the distance across the gap before meeting the other streamer. This gives an actual velocity of about one-tenth of the velocity of light.

With such a high velocity of progress of the streamers a surge, no matter how steep, does not rise to much over the 60 cycle value before the flashover takes place between the spheres. Consequently, the sphere gap has practically unity impulse factor for all waves that can be produced artificially, and since artificial waves of higher steepness than those encountered in service can be produced, the sphere gap has unity impulse factor for all lightning waves. The velocity of propagation of this phenomenon appears to be dependent on the average value of the gradient between the spheres. Consequently, the steeper the wave front the greater the velocity.

The same phenomenon occurs on a string of insulators, except that, on account of the fact that the average gradient along the string at flashover is much less than in the case of spheres, the velocity of propagation of the streamer is much slower. On a string of five units, it has been estimated from actual tests to be of the order of one-fiftieth the speed of light. The impulse flashover of a five unit string for waves of different steepnesses has been calculated on the basis that with a very slow wave front, the speed of propagation of the streamers is one-fiftieth the speed of light and that this speed is increased in proportion to the increase of potential. The curve *A*, Fig. 4 has been calculated on this basis. The dotted line *B* shows the actual curve obtained from test. The correspondence is very close and within the limit of errors of observation. The upper curves of Fig. 4 were worked out for a 14 unit string of insulators. The curve *C*, appears to be substantially in agreement with values that have been obtained on lines. All these curves are subject to revision as knowledge of the art of measuring and recording surges progresses.

The steepest wave front observed in lightning flashovers is about 4000 kv per microsecond. A 14 unit string with a surge of this steepness, having a high crest value, will flash over at 2000 kv. Its normal 60 cycle flashover is 1170 kv, so that its impulse factor to this wave would be about 1.7. If such a wave, having a crest value well above 2000 kv, were to be induced on a transmission line, the insulator would flash over at 2000 kv, quickly reducing the surge to about zero po-

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tential, so the wave which would hit the substation would have a crest value of 2000 kv. This would be reached in half a microsecond and attenuated very rapidly to a negligible value. Such a wave, by the time it reached the transformers, would be further reduced in crest after it struck the condenser terminal, so that the value of the surge when it reached the transformer winding probably would be reduced to not much over the 60 cycle flashover value of the insulator string. This would not break down a transformer in good condition, as the time lag of breakdown of oil and insulation is very much greater than that of air.

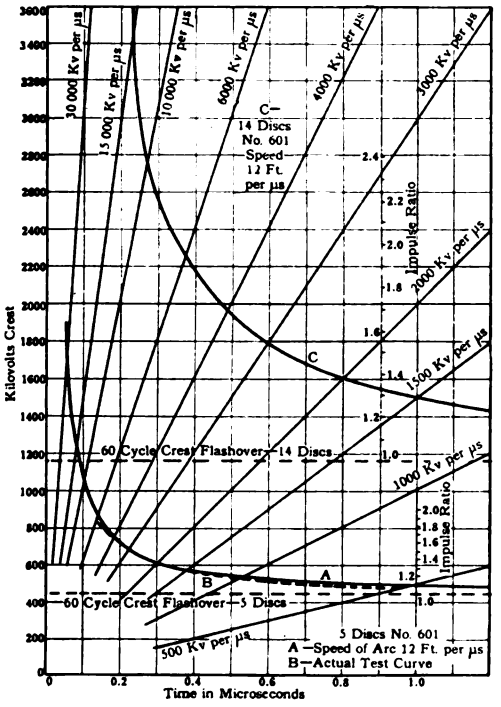


FIG. 4—INSULATOR FLASHOVER CURVES

From the explanation of the mechanism of flashover as given in the previous article follow two important points:

1—When the surge has reached a value equal to the crest value of the 60 cycle flashover of the string of insulators, the field around the insulator string starts to become highly conducting.

2—If the 60 cycle crest value is maintained, it is only a matter of time before the insulator string will flash over.

This time preceding flashover varies with the type of insulator. The longer the arc distance, the greater will be the time required. Other factors enter in, such as the barrier effect, etc., which further increase the time required to produce the flashover. Since it is only a matter of time before flashover takes place, when the 60 cycle crest value of flashover is reached, it will be obvious that a surge which flattens out at the 60 cycle crest value will flash over the insulator string provided it stays at the 60 cycle crest value for an appreciable length of time. Many lightning surges will have this characteristic, i.e., they will reach the 60 cycle crest value of flashover of the insulator string or go slightly beyond this and will attenuate quite slowly. If such a wave should just reach the 60 cycle flashover value and immediately recede, no flashover will take place, i.e., the flashover will be repressed. On the other hand, if the wave should get slightly above the 60 cycle crest value and remain above for an appreciable time, say for one-half a microsecond, the insulator string will flash over. Consequently, the impulse factor, or the ratio of the impulse flashover voltage to the 60 cycle crest value of flashover, of an insulator string for a lightning surge of a given steepness will vary from unity to 1.8. It will be unity for waves no matter how steep which flatten out slightly above the 60 cycle crest value. It will be 1.8 for the steepest lightning waves provided such waves keep on rising at the same rate to values well above double the crest value of 60 cycle flashover.

It will be evident from this that we must be very careful in specifying impulse ratios. An impulse ratio means little unless we have all the specifications of the applied surge. However, since we are concerned with the possible effect of surges of great magnitude on substation apparatus, we usually find it convenient to consider impulse factor in connection with a chopped wave. A chopped wave is the result of a wave having a crest value several times that of the 60 cycle flashover of the insulator which it strikes, and which is chopped by the resulting flashover of the insulator. With this type of wave the impulse factor of the insulator will depend upon the slope of the original wave after the 60 cycle flashover value has been reached. This subject is mentioned again to emphasize that the importance of impulse factor in line insulation is not because it affords a factor of safety against insulator flashover due to surges, but because it affords a factor of safety to the substation apparatus when high impulses due to direct lightning strokes hit the line. The insulators then will break down at a moderate voltage and protect the apparatus. The idea that high impulse flashover is desirable in transmission line insulation is erroneous. However, it would not be safe to raise the 60 cycle flashover value to the same value as the impulse value for fear of endangering the substation apparatus.

Where it is desirable to insulate the line to prevent outages, extra insulation may be used on a portion of the line, say one-fourth of a mile adjacent to substations. This will be sufficient to protect the substations against abnormal lightning surges.

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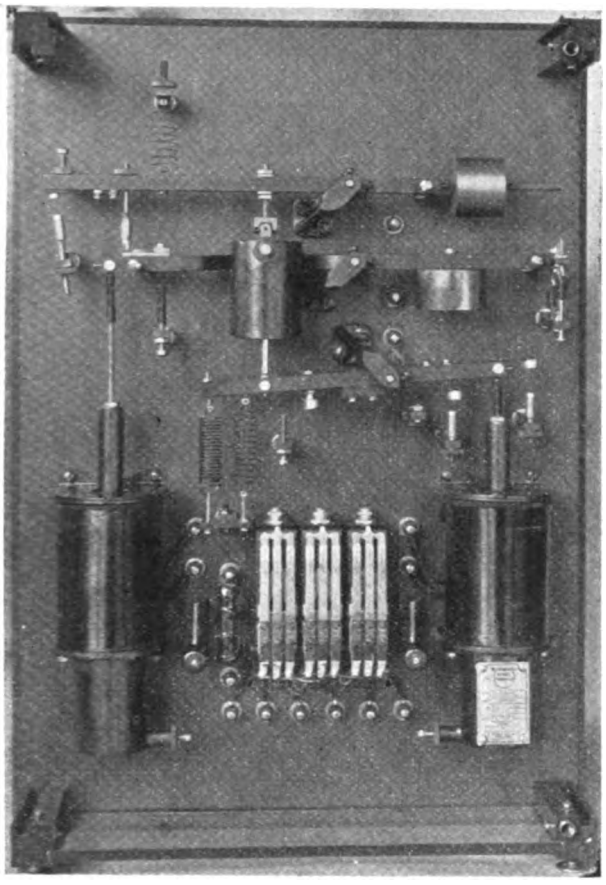
FIG. 1—THE AUTOMATIC SYNCHRONIZER



# A New Automatic Synchronizer

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Westinghouse Electric & Mfg. Co.

Automatic synchronizing has been in commercial use in connection with automatically controlled water-wheel generators for several years. By reason of the accuracy with which synchronizing is thus accomplished; because of the lessened disturbances and lower surges caused on the transmission lines to which the generators are connected; and also because of the lessened possibility of damage to station equipment, the interest of engineers has been aroused in the subject of automatic synchronizing for the larger and larger stations, even where attendants are available. This increasing interest has resulted in the development of an automatic synchronizer working on an entirely new principle, which is discussed in the following article.

WHEN two synchronous generators are to be connected in parallel, the equalizing current between them will be zero if, when the connecting breaker contacts engage: 1—the voltages are equal; 2—the phase displacement between the voltages is zero; 3—the frequency difference is zero. The voltage equality will have to be taken care of by some sort of a voltage regulating device outside the automatic synchronizer, and will therefore not be discussed here. This is often accomplished by a simple fixed resistance in the field circuit during the starting period.

*Zero Phase Displacement*—The equalizing current will be proportional to the sine of the angle of phase displacement between the two voltages at the moment when the circuit breaker contacts engage. The performance of an automatic synchronizer can therefore be judged by checking this angle of phase displacement.

*Zero Frequency Difference* is of a merely theoretical interest, because it can not be obtained within a reasonable time in the majority of practical applications. Consider a case where a generator is to be paralleled to a transmission line. By means of a speed matcher acting upon the governor mechanism of the prime mover, the generator is brought up very close to synchronous speed. With an ideal speed-matching equipment and with a constant line frequency it would be possible to obtain a frequency difference equal to zero. In this case the ideal synchronizing conditions would prevail at the instant when the phase displacement between the voltages was zero.

In practice, however, the sensitivity of the speed-matching equipment is not absolute, and speed variations may occur, due to the inherent characteristic of the prime mover as well as change in line frequency. For these reasons, in most practical applications, it is often not possible to match a machine against a constant line frequency to give absolute zero frequency difference. With a good speed-matching equipment the machine can be brought so close to the synchronous speed that the phase displacement of the machine voltage in relation to the line voltage will be within a range of 90 degrees lag to 90 degrees lead. The synchroscope may then be swinging back and forth within this range, and there will be zero frequency difference each time the increase in phase displacement changes from leading to lagging.

The frequency of most transmission lines changes very slightly due to load variations. These frequency variations will further decrease the probability of obtaining zero frequency difference at the same time the zero phase displacement occurs.

If an automatic synchronizer was designed to operate only when the frequency difference was zero,

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the apparatus would be ideal from a theoretical view point; but it would be prohibitive in any practical application, because it would take too long to get the machine connected to the line. For most applications the synchronizer probably never would get an opportunity to close the circuit breaker, as an exact zero frequency difference would necessitate the machine staying in synchronism long enough to get the breaker closed.

Fortunately, however, in actual practice, exact zero frequency difference is not necessary. Small generating units can be safely paralleled with transmission lines even if the frequency difference is one quarter cycle per second, provided the phase displacement is zero. Larger ones require a smaller frequency difference. Thus, the time necessary to connect the machine to the line can be considerably reduced.

The underlying idea of an automatic synchronizer is therefore to provide a means of paralleling two alternating-current sources as soon as the frequency difference is below a certain value, to be chosen for each particular application; and to make the circuit breaker contacts engage at the moment when the angle of phase displacement between the two voltages is zero. This latter feature requires that the time required to close the circuit breaker be considered.

*The Time Element of the Circuit Breaker*—There is a definite time element between the moment when the contacts of the synchronizer energize the

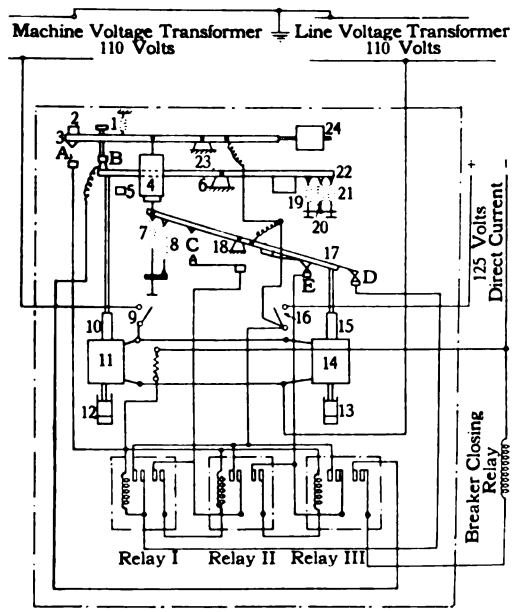


FIG. 2—SCHEMATIC ARRANGEMENT OF THE AUTOMATIC SYNCHRONIZER

intermediate relay which energizes the closing coil of the circuit breaker, and that when the main contacts of the breaker close. This time element is practically constant for a certain breaker application, but will vary from 0.2 to 0.6 seconds with different types of circuit breakers.

If it is desired to connect a machine to a line through a circuit breaker having a time element of 0.5 second, then, to get the main contacts of the breaker to close at the point of zero phase displacement, the contacts of the synchronizer will have to close earlier than the moment of zero phase dis-

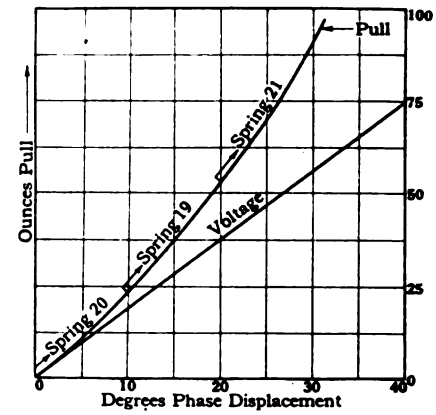


FIG. 3—VARIATION OF VOLTAGE AND CORE PULL WITH PHASE DISPLACEMENT

placement by an amount depending upon the frequency difference. The advance in degrees will be proportional to the frequency difference. Thus

$$A = 360\ F\ T.$$

where, $A$ = degrees advance.
$F$ = frequency difference, in cycles per second.
$T$ = time element of breaker, in seconds.

## THE CHIEF REQUIREMENTS OF AN AUTOMATIC SYNCHRONIZER

The requirements to be met by an automatic synchronizer can be summed up in the following points:—

1—The synchronizer must close its contacts at a certain phase advance which must be proportional to the momentary frequency difference. By a single adjustment it must be possible to vary the amount of advance to suit different circuit breaker applications.

2—The synchronizer must operate only within a prescribed frequency difference. The operating range must be made adjustable by a simple adjustment feature.

## PRINCIPLES OF OPERATION

The appearance of the new automatic synchronizer without the case is shown in Fig. 1, and the schematic diagram of the equipment is shown in Fig. 2. The functioning of the synchronizer centers about the operation of two coils 11 and 14 which are connected in parallel across the beat voltage. Coil 11 and its connected equipment prevents the main circuit breaker from being closed except when the two machines are in synchronism. Coil 14 and its associated levers prevents the closing of the circuit breaker when the difference between the two frequencies is excessive.

While this equipment can be used to synchronize adjacent generators in the same power house, as well as to synchronize a generator with a transmission line, for simplicity in discussion the latter condition

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will be assumed throughout this article. Provided both the line and machine voltages are sine waves, the voltage across the coils will vary as a sine curve. When the phase displacement between the line voltage and the machine voltage is zero, the voltage across the coils is zero, and consequently the pull on cores 10 and 15 is zero. With 180 degrees phase displacement, the voltage across the coils and also the pull on the cores is maximum.

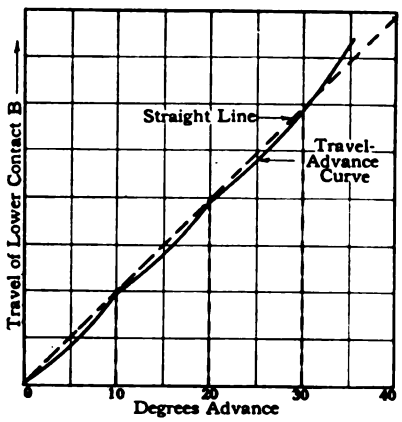


FIG. 4—CONTACT TRAVEL WITH ADVANCE

*The Phase Angle System*—Core 10 which is supported by the lever 22 pivoted to the fulcrum 6, is balanced against springs 19, 20, 21 so that the travel of the lower contact *B* is proportional to the phase displacement in degrees. Without any springs and with zero voltage across coil 11 there is a small overweight on the core side of the lever 22. Spring 20 is adjusted so that contacts *B* just touch when the voltage across the coil is zero and lever 3 is pulled up against the stop 2.

For varying phase-displacement, the voltage across the coil changes with the sine of the angle of phase-displacement. This means that for small angles of phase-displacement the voltage increases approximately along a straight line, as shown in Fig. 3. However, because the pull on the core increases when the core travels farther into the coil, the pull does not vary in the same manner as the voltage, but differently, as shown also in Fig. 3. For this reason it is necessary to apply the springs 19 and 21 which come into action in sequence and give a travel-advance curve very close to a straight line, as shown in Fig. 4.

To dampen the vibration due to the frequency of the alternating-current, an air dashpot 12 is applied. The damping of this dashpot is very small, and for this reason the core, and, therefore, also the lower contact *B* assume a position in relation to the highest position of the upper contact B dependent only upon the phase displacement between the line and machine voltages, and independent of frequency difference.

*The Advance Lever System*—There is a time interval between the energizing of the coils of a circuit breaker and the closing of its contact for which the synchronizer must provide. To obtain an advance closing of the synchronizing contacts *B*, is the function of coil 14, Fig. 2, with core 15, levers 3 and 17, the dashpot 4 and the springs 1, 7 and 8. The springs 7 and 8 are adjusted to give a travel of the core 15 which is proportional to the phase-displacement. At 180 degrees phase displacement the voltage is maximum (220 volts) across the coil, and the core will be pulled down in the lowest position against a stop provided by the contacts *E*. When the phase displacement decreases, the voltage across the coil decreases, and finally at 130 degrees phase displacement the pull on the core is equal to the tension of the springs 7 and 8. If the phase displacement is further reduced, the core will start to travel upwards, following a travel-advance curve shown in Fig. 5.

Since upper contacts *D* and *E* are spring-mounted, the contacts will remain closed during the first part of the upward travel of core 15, as shown in Fig. 5. The contacts will open when the phase displacement is 100 degrees. In the same manner, since the lower contact *C* is spring mounted, the contacts *C* will close at 30 degrees, and remain closed, while the core reaches its highest position at zero degrees.

The total travel of the core is completed between 130 degrees phase displacement and zero phase displacement. Because the time necessary for the phase displacement to change a certain number of degrees will be inversely proportional to the frequency difference, the speed of the moving core will be proportional to the frequency difference.

Air dash pot 4 is suspended from lever 3, while its plunger is connected to lever 17. This plunger will move down when the phase displacement is decreasing, the speed of travel of the plunger being proportional to the frequency difference. This can be illustrated by an analogy, as in Fig. 6. Suppose a dashpot *A*, connected to a lever *B* is balanced by

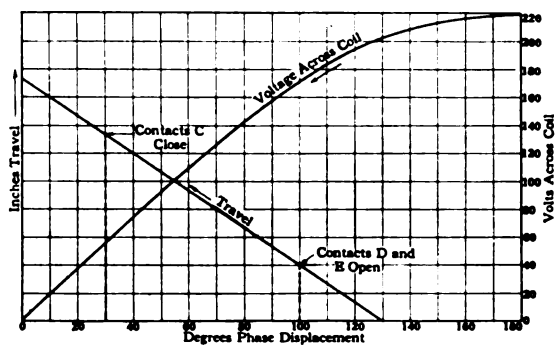


FIG. 5—THE CORE TRAVEL-ADVANCE CURVE

means of a counter-weight $G_1$. In the balanced position the tension on the string *D*, connecting the lever *B* to a rigid point *E* is zero. The dashpot plunger *F*, connected to the lever *H* is balanced against the counterweight $G_2$.

If a downward force *P* is applied to the plunger *F* the plunger will move down with the velocity $v = P/k$, where $k$ is a constant dependent upon the setting

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of dashpot air valve. The reactive pull $P_1$, on the lever $B$, equal to the tension on the string $D$ is equal to the applied force $P$ or: $P_1 = P = Kv$. In other words, the tension on the string $D$ will be proportional to the velocity of the dashpot plunger $F$.

If the string is replaced with a spring, the left side of lever $B$ will move downward until the tension on the spring is equal to $P_1$. The elongation of the spring, and the downward movement of the left side of lever $B$, will therefore be proportional to the velocity of the plunger,—and in our application proportional to the instantaneous frequency difference.

In Fig. 2, lever 3 is balanced against the stop 2 by means of the counterweight 24 and the spring 1, when the velocity of the plunger 4 is zero. When the plunger is moving downward with a certain velocity, spring 1 will be extended, due to the pull of the dashpot, and since the extension of the spring is proportional to the pull on it, the travel of the upper contacts $A$ and $B$ will be proportional to the pull on the dashpot, and accordingly proportional to the frequency difference, as shown in Fig. 7.

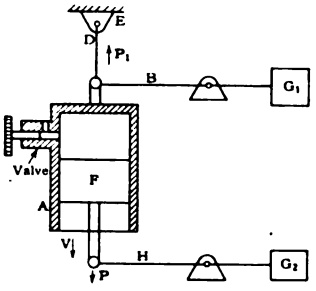


FIG. 6—ANALOGY SHOWING SYNCHRONIZER AIR DASH POT ACTION

Because core 15 starts to travel at 130 degrees phase displacement, upper contacts $A$ and $B$ will have assumed a certain definite position, dependent upon the frequency difference, when the lower contact $B$ starts to travel upward from stop 5 and thus the contacts $B$ will close in advance of synchronism by a definite amount.

In Fig. 7 are shown the travel-advance curve for the lower contact B as well as two different travel-frequency curves for the upper contact $B$. The slope of the last mentioned curves can be varied by tightening the air valve of the dashpot 4. The curve marked $K_1$ corresponds to a tighter air valve (and slower breaker) than the curve marked $K_2$.

Assume that a slow breaker is to be closed at synchronism; and that the incoming machine is faster or slower than bus frequency by 1/16 cycle per second. As synchronism is approached, first upper contacts $A$ and $B$ on arm 3 are quickly moved downward. At a balance between spring 1 and the pull of coupling dashpot 4, upper contacts $A$ and $B$ are held at a position on line $X$-$Y$. Then lower contact $B$ begins to move upward. When it has reached the line $X$-$Y$, that is, when the synchronizing contacts close, the phase displacement or advance is 35 degrees early. While the machines are coming into synchronism from this 35 degree point, the breaker mechanism and associated relays are operating, and the breaker line contacts close just at synchronism.

If the frequency difference were 1/8 cycle per second, then upper contacts $A$ and $B$ would endeavor to reach line position $X'$-$Y'$ corresponding to a 70 degree advance. Obviously 70 degrees is too great an advance, because there is too great an opportunity for

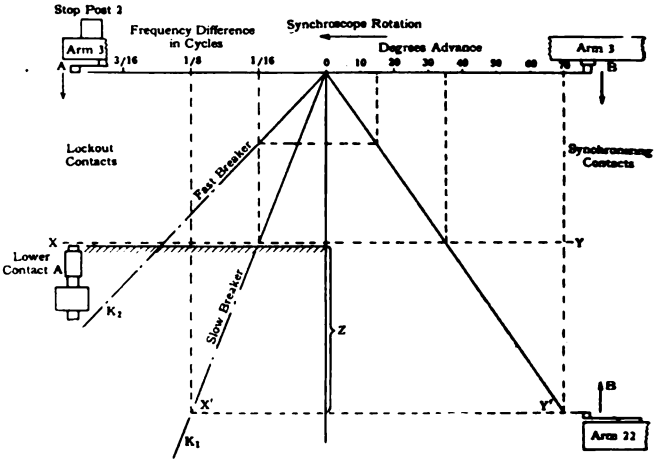


FIG. 7—CONTACT TRAVEL RELATIONSHIPS

conditions to change during such an interval. Therefore, lower lockout contact $A$ is adjusted so that the lockout contacts close first, while synchronizing contacts $B$ are still open a distance $Z$, thus preventing the breaker from closing until the frequency difference has been reduced sufficiently. If lower lockout contact $A$ is adjusted upward to reach line $X$-$Y$, then it is obvious from Fig. 8 that for the slow breaker lockout occurs at a frequency difference of 1/16 cycle per second, and the maximum advance is 35 degrees.

A frequency difference of 1/16 cycle per second requires 16 seconds per revolution of the synchroscope. At 360 degrees in 16 seconds, 35 degrees would require 1.55 seconds. These values of course do not represent commercial breaker equipment, but serve to illustrate the principle. Similarly the fast breaker closes in 15/360 of 16 seconds, or 0.67 seconds. Operation with a fast breaker at a frequency difference of 1/16 cycle per second gives the required smaller advance of 15 degrees instead of 35 degrees for a slower breaker. As previously described, the coupling dash-

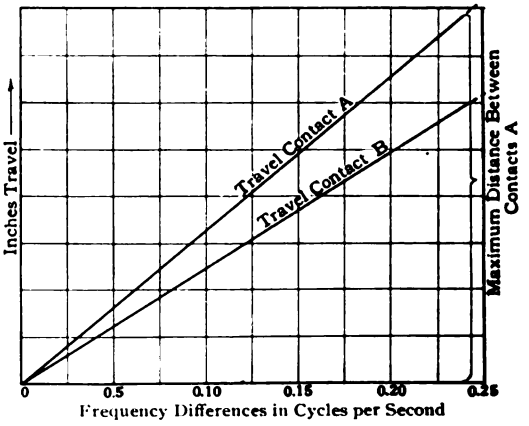


FIG. 8—TRAVEL-ADVANCE AND TRAVEL-FREQUENCY CURVES FOR CONTACTS A AND B

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pot needle-valve setting calibrates the synchronizer for the speed of the breaker being handled.

METHOD OF ADJUSTMENT

One of the exceptional features of the new automatic synchronizer is its easy adjustability. When the synchronizer is shipped from the factory, the air valve of dashpot 4 is set to give an advance closing of contacts *B* corresponding to a 0.5 sec. breaker. The lower

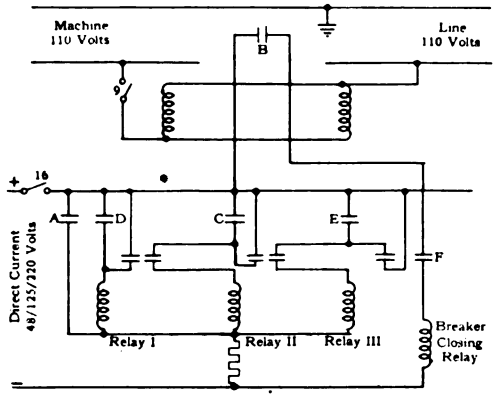


FIG. 9—SCHEMATIC DIAGRAM OF SYNCHRONIZER CONNECTIONS

contact *A* is set to lockout and prevent the circuit breaker from closing for frequency differences above 1/6 cycle.

*The Advance Adjustment*—For most applications the exact closing time of the circuit breaker is not known. The synchronizer is connected to operate and close the main circuit breaker while the disconnecting switch between the machine and the line is open. By hand control the machine speed is regulated to give 1/10 cycle frequency difference between the machine and the bus. At this frequency difference the synchroscope will make one revolution in 10 seconds.

A lamp with a small time lag, or a quick acting relay is connected in series with one pair of the breaker main contacts, and is energized by the direct-current control source. This lamp or relay is placed close to the synchroscope to indicate the moment when the breaker contacts engage. If the breaker contacts close when the synchroscope pointer is off synchronism, the setting of the air valve of dashpot 4 is changed. Tightening the valve screw will advance the closing point.

*The Lock-Out Adjustment*—The machine speed is adjusted to give the highest frequency difference at which the synchronizer should close the breaker. At this frequency difference the lower contact *A* is adjusted so that the apparatus is just not locked out.

OPERATION

In Fig. 9 is shown the schematic diagram for the synchronizer. Assuming that the proper connections to the machine have been made, the first step in synchronizing is to close switches 16 and 9. If the frequency difference is high, say 5 cycles, none of the relays I, II and III will be energized, because lever 17, Fig. 2, due to the damping effect of dashpots 4 and 13, will never come into a position to close the contacts *D*.

When the frequency difference is reduced to about 3 cycles, contacts *D* will just engage at 180 degrees in advance of synchronism. Relay I will then close and its auxiliary contacts form a holding circuit, and establish the circuit of relay II through *C*. At this frequency difference, however, the relay coil will be short-circuited by contacts *A* and the relay will be opened at a point about 70 degrees in advance of synchronism.

If the frequency difference is further reduced to 1.5 cycle, contacts *C* will be engaged, and close relay II at zero degrees, provided relay I is already closed. The frequency difference is still too high for synchronizing and for this reason the relays will be locked out by the contacts *A*.

When the frequency difference is lowered to, for example, 1/7 cycle and the contacts *A* are set just not to engage at this frequency difference, the contacts *E* will close relay III 260 degrees ahead of synchronism. Relays I and II having been closed on earlier beats, the breaker closing relay will be energized when the contacts *B* close at a certain advance. If, however, the difference in frequencies should happen to increase above the safe synchronizing limit, in this case supposed to be 1/7 cycle, then all three relays will be opened by the contacts *A* before contacts *B* engage, and the breaker will not be closed.

In Fig. 10 are shown schematically the parts of the successive beat cycles on which the different relays close their contacts. Relay I and III will close their contacts 260 degrees in advance when the frequency difference is below one cycle, and relay II will close at

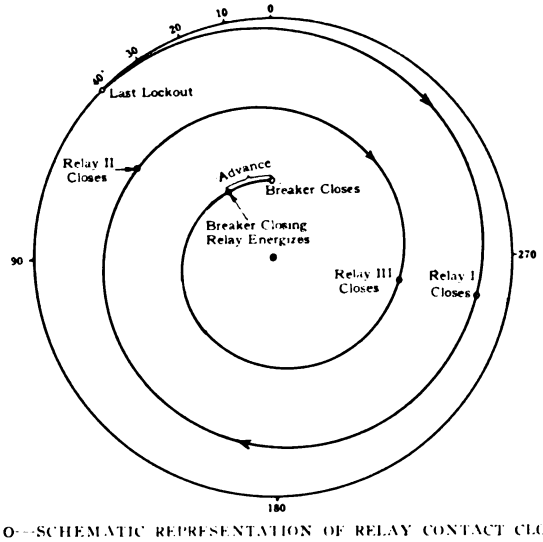


FIG. 10—SCHEMATIC REPRESENTATION OF RELAY CONTACT CLOSURES

50 degrees. When the frequency difference is increased above one cycle the point of closing of relays I and III moves rapidly toward 180 degrees with increasing frequency difference, and for frequency differences above three cycles, relays I and III will not be energized during the beat. In the same manner the point of advance where relay II is energized with in-

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creasing frequency difference will move towards zero, and for frequency differences above 1.5 cycles, relay II will not become energized. This feature provides the apparatus with a double lockout for frequency differences above 1.5 cycles:—one lockout by the closing of contact *A*; another by the failure of contacts *C* to close.

### COMPARATIVE TESTS BETWEEN HAND AND AUTOMATIC SYNCHRONIZING

A 3000 kv-a, 25 cycle, three-phase motor-generator set was arranged to be synchronized with a 25 cycle test circuit with the connections shown in Fig. 11. The frequency of the test circuit showed some variations due to variable load. Synchronizing was done with the above described equipment; and also by hand operation performed by an experienced operator.

*Measurement of Closing Time*—With a cycle counter the time interval from the closing of contacts *B* until the circuit breaker contacts engaged and closed an indicating relay was found to be 0.6 sec.

*Arrangement of Tests*—The speed of the motor-generator set was regulated by hand to give various beat frequencies, and the lock-out contacts on the synchronizer were set to lock-out for frequency differences above 1/7 cycle. A very quick operating indicating relay was used (closing time 0.009 sec.) which would close its contacts practically when the circuit breaker contacts engage. This indicating relay was held in the hand of one of the men conducting the tests, and the position of the synchroscope pointer was read by him at the instant when he felt the indicating instrument operating.

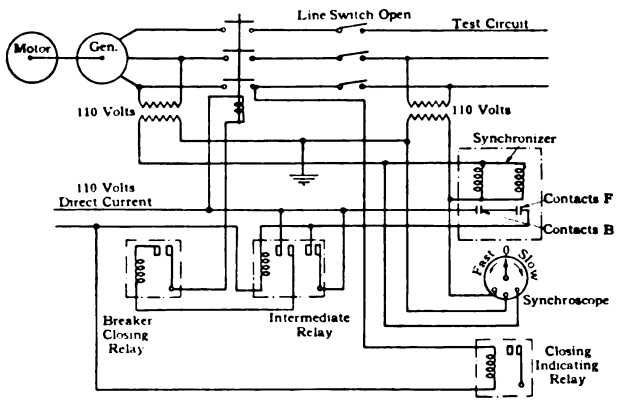


FIG. 11—CONNECTION FOR COMPARATIVE TESTS

With the automatic synchronizer in operation 193 readings were taken; and 67 readings were taken with hand operation. The results of these tests, as plotted in Fig. 12, show the superior accuracy of the automatic synchronizer, as compared with the performance of an experienced operator, synchronizing by hand. The most inaccurate automatic closures were due to deceleration inside the synchronizing zone, after the circuit breaker closing coil had been energized (early limit); or to the synchroscope hanging outside of the synchronizing zone and then accelerating through synchronism (late limit).

The same results are plotted in a different way in Fig. 13, the curves of which show the percentage of total number of operations for which the circuit breaker contacts were closed within a certain number of degrees of synchronism. For example, with automatic synchronizing the circuit breaker contacts closed

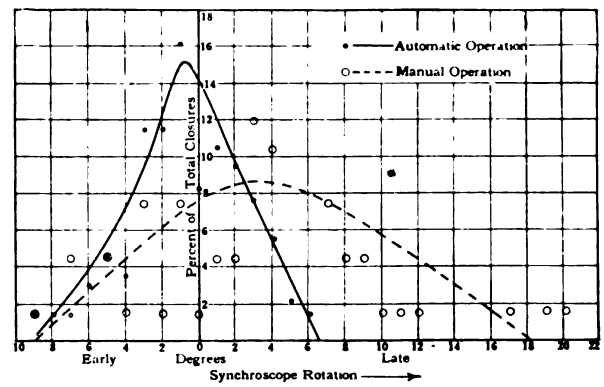


FIG. 12—RESULTS OF COMPARATIVE TESTS

two degrees or less off synchronism for 56 percent of the total number of operations; while with hand operation the operator succeeded in getting equally good results for only 19 percent of the total number of operations. These curves fail to indicate the fact that automatic closure required much less time than hand closure. In other words, the operator always waited for a smaller frequency difference before closing the circuit breaker than did automatic synchronizer. In spite of this fact it is seen that the automatic synchronizer never closed the circuit breaker farther off the point of zero phase displacement than nine degrees, while the operator, choosing his own best speeds slower than automatic operation, happened to close the circuit breaker as much as 20 degrees off in one instance and more than 15 degrees off in several cases.

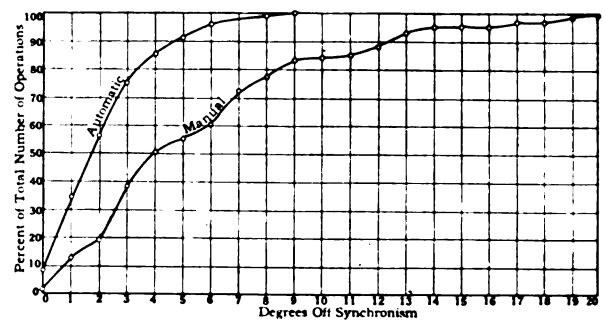


FIG. 13—A COMPARISON OF AUTOMATIC AND MANUAL SYNCHRONIZING

From these curves it is evident that the automatic synchronizer is more reliable and quicker than a skilled operator. The more accurate synchronizing materially reduces the shock to the generator and connected apparatus.

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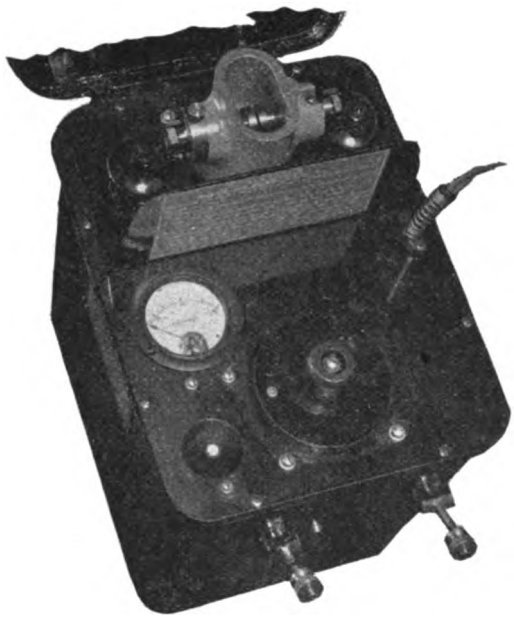

Testing of electrical insulating oil can now be done with uniform increase of voltage.

# A New Portable Oil Testing Set

A. M. WIGGINS
Transformer Engineer,
Westinghouse Electric & Mfg. Co.

IT is of prime importance that insulating oils be kept free from water and other impurities. Tests have shown that as little as 0.005 percent of moisture will reduce the dielectric strength of oil to about one-half of its strength when dry. The curve in Fig. 1 shows the effect of moisture in insulating oils.

In order to make sure that the dielectric strength is up to its proper value, the insulating oil in any piece of apparatus should be tested at regular intervals. The N.E.L.A. recommends that oil samples from all power station and substation apparatus be tested at least once every three months, and that samples from distribution transformers be tested at least once a year. A standard test for insulating oil is made between two disc electrodes 1 inch in diameter and spaced 0.1 inch apart with their flat surfaces opposite and parallel. With this arrangement good insulating oil will average 22 000 volts or better on breakdown tests.

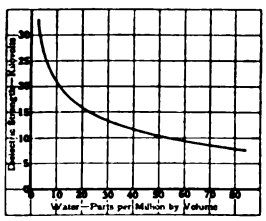

FIG. 1—THE EFFECT OF WATER ON INSULATING OIL.

Many users of transformers and large circuit-breakers do not have the necessary equipment for testing insulating oils. To meet this need there has been developed a new, small, portable, oil testing set which accurately determines the dielectric strength of insulating oils up to 25 000 volts. The principle used in this set* is unique in its operation.

*Based on an invention of Mr. J. F. Peters.

In many cases where it is desired to obtain variable voltages from one transformer for testing purposes, the procedure is to place taps in the primary winding and switch the constant, impressed voltage between these taps. This varies the volts per turn, and hence the value of the secondary induced voltage, which is necessarily limited to steps. In switching between taps the primary winding is alternately disconnected and reconnected to the supply voltage. This results in high initial currents which are undesirable and which cause serious voltage wave distortions. These voltage distortions may be of such a nature that erroneous readings of oil failures are observed. The insertion of a resistance in series with the primary winding does not always remedy the situation.

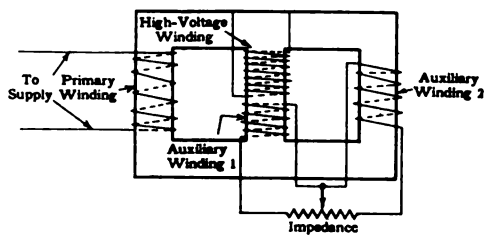


FIG. 2—SCHEMATIC DIAGRAM OF THE TRANSFORMER AND CONNECTIONS

In the new set just developed, the difficulties due to high starting currents and distorted voltage waves have been eliminated. A schematic diagram illustrating the principle used in this set is shown in Fig. 2. The magnetic circuit consists of three legs, as in a three-phase core-type transformer; the exciting or primary winding is wound on one outside leg, the high-voltage or testing winding is wound on the middle leg with one auxiliary or control winding, and one auxiliary winding on the other outside leg.

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When a voltage is impressed on the primary winding, a flux is established in the core. The flux has two parallel paths through the two legs not embraced by the primary winding. By varying the amount of impedance connected across each auxiliary winding, the division of flux between the two legs may be adjusted. When the impedance across auxiliary winding 1 is reduced to a minimum, i.e., the winding is short-circuited, very little flux links that winding, and consequently only a very small voltage is induced in the high-voltage winding. As the impedance across auxiliary winding 1 is increased and that across auxiliary winding 2 decreased, more flux links the high-voltage winding and less links the auxiliary winding 2. By making the value of the impedance between the two auxiliary windings fairly large and of a large number of steps, the flux may be caused to shift between the middle and outer legs in such a manner as to give a smoothly increasing voltage induced in the high-voltage winding.

An oscillographic record of the primary or impressed voltage and the voltage induced in the high-voltage winding is shown in Fig. 3. This oscillogram was taken while raising the induced voltage in

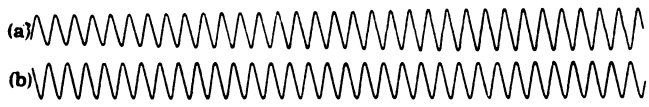


FIG. 3—AN OSCILLOGRAM TAKEN DURING THE INCREASING OF THE SECONDARY VOLTAGE

(a) Secondary voltage. (b) Primary voltage

the high-voltage winding and shows the gradual increase.

## DESCRIPTION OF SET

The complete set is mounted in a cast aluminum case and comprises, in addition to the transformer, a double-pole self-restoring push switch, a control rheostat, a portable plug for connecting to an ordinary 110 volt light socket, a voltmeter calibrated in kilovolts, and an oil test cup fitted with standard testing electrodes and a feeler gage for setting, all of which are mounted on a panel at the top and inside of the case. Two views of the assembled oil test cup are shown in Fig. 4. The voltmeter is mounted flush with the panel and is connected to auxiliary winding 1. It is calibrated to read the voltage induced in the high-voltage winding. The rheostat control is similar to the usual panel-type rheostat and has one operating arm. The cover of the case is hinged at one side and held down with thumb nuts at the other. It may be removed entirely, as with a standard meter case cover. The mid-point of the high-voltage winding and the control circuit are grounded to the case, thereby decreasing the insulation stresses and insuring highest safety to the operator.

## OPERATION OF THE SET

When making a test the oil test cup is thoroughly cleaned out, and the gap set with the feeler gage. The cup is filled with the sample of oil to be tested, the oil level being one inch or more above the electrodes. Before making the test the oil is allowed to settle.*

When the test cup has been properly adjusted, the case is grounded to insure full protection to the operator, and the line plug attached. The rheostat control is then set on the *start* position, the push

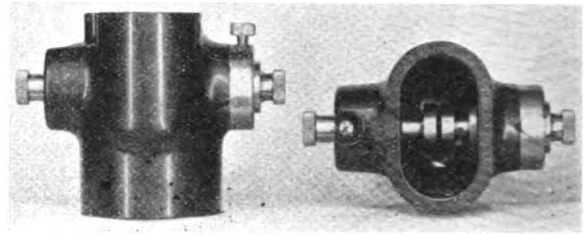

FIG. 4—A SIDE AND A TOP VIEW OF THE OIL TESTING CUP

switch closed, and the rheostat control arm moved forward until the test cup flashes over. During this cycle, the voltmeter reads the equivalent of the test voltage, and the value of the oil failure is thereby observed. When the test cup flashes over, the push switch is released and the rheostat control returned to the *start* position. The cycle may be repeated as often as necessary. The arrangement of the apparatus permits rapid testing with a high degree of accuracy.

*For a more detailed discussion of oil testing, see an article "Electrical Insulating Oil" in the JOURNAL for Feb. and March, 1928.

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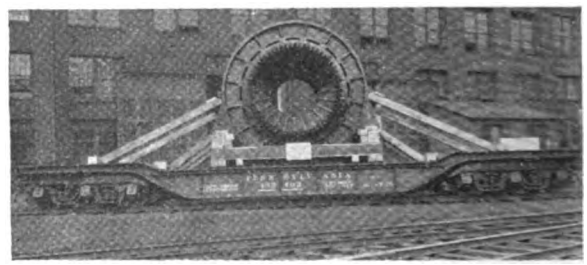
INDICATIVE of the trend in the electrical industry for ever larger and larger apparatus, are the three new flat cars built by the Pennsylvania Railroad for hauling heavy machines. The weight and clearance limits of the largest existing cars had been reached. But electrical machinery has kept on growing, making it necessary to ship large generators, motors and the like, unassembled, sometimes even in halves. This involves assembling, winding, and testing such machines



A 252 000 LB. CAPACITY FREIGHT CAR

after they are in the field, not at all a satisfactory condition, as facilities are much better and cheaper at the manufacturing plant.

To meet this problem three cars, completely redesigned, have been built to care for these great weights and sizes. The difficulties of this problem were accentuated by the fact that the load is not evenly distributed over the car but is concentrated in the center. In addition, to permit greater machine heights, the center of the car is depressed. This feature is not new but adds to the difficulties of supporting these heavy loads.

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# Fluid Governors for Prime Movers

## III—Operating Mechanism

HENRY F. SCHMIDT

BEFORE discussing the types of operating mechanisms, a paragraph or two on governing requirements may not be amiss. The function of a governor is to maintain the speed constant within certain limits. It is not possible, however, to make a governor which will maintain the speed constant from no load to full load, or isochronous, as there would be no determining factor to control the admission of motor fluid. Prime mover turbines are usually specified to have a certain variation of speed between no load and full load, which may be fixed at any value between one-half and four or five percent, the more usual speed variation specified being four percent. Generally speaking, the wider the speed variation allowed the more stable the governing mechanism regardless of what type it may be. A certain amount of speed variation is also required in order that alternators running in parallel may operate satisfactorily and maintain proper load distribution.

In Fig. 20, is shown, diagrammatically, the pump impeller of an oil governor which, for convenience, will be considered to deliver oil at 100 pounds pressure at 100 r.p.m. The oil is delivered to an operating cylinder having a piston of 10 square inches which is balanced by a spring and controls a valve having a total travel of one-half inch. Assume that this governor is to have a speed variation of four percent between no load and full load, the no-load speed being 100 r.p.m., the full-load speed 96 r.p.m.

Since the pressure of the centrifugal pump varies as the square of the speed, a decrease of four percent in speed causes a decrease of approximately eight percent in the discharge pressure, or eight pounds per square inch. The total load which must be carried by the governor spring opposing the piston will be 10 square inches by 100 pounds or 1000 pounds. The change of load on the spring for a four percent change of speed will be 80 pounds. Since this change of 80 pound load occurs with a travel of one-half inch, or at the rate of 160 pounds per inch of travel, the scale of the spring required would be 160 pounds, the scale of a spring being the number of pounds required to compress or extend it one inch. As the initial load on the spring is 1000 pounds, and it will compress one inch for 160 pounds, the initial stretch of the spring will be 6.25 inches or 1000 divided by 160.

Now, if the speed variation required had been specified at one percent instead of four percent, the change of pressure between no load and full load would be only two percent or two pounds and the change of load on the spring would be 20 pounds, which must occur in one-half inch travel. Consequently, the scale of the spring required for one percent speed variation would be 40 pounds, requiring an initial stretch of 1000 divided by 40 or 25 inches. It is obvious that such a spring would be impracticable, since a compression spring would buckle and a tension spring would be inconveniently long. The difficulties of designing such a direct-acting governor would be increased if the valve travel required were greater. For instance, if the valve travel were two inches instead of one-half inch in the first instance, with four percent speed variation, the change of 80 pound load would take place in two inches, or the scale of the spring would be 40 pounds, or the same as for the case of one percent speed variation with one-half inch travel. If two inches travel were required with one percent speed variation, the initial stretch of the spring would be 100 inches.

From consideration of the above problems, it seems obvious that in order to obtain a powerful governor without getting into excessive and unmanageable

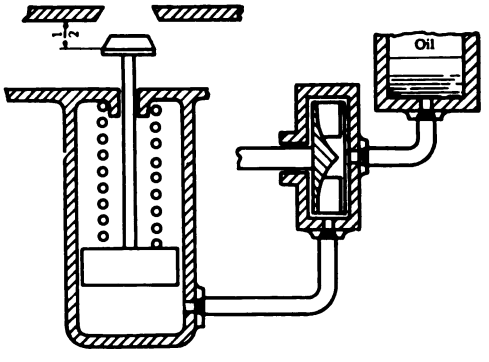


FIG. 20—A DIAGRAMATIC SKETCH OF A SIMPLE OIL GOVERNOR

spring proportions, an oil relay must be resorted to. Fig. 21 shows a simple oil relay consisting of a cylinder *A* with an operating piston *B* and a relay sleeve *C*. A port *D*, communicates with the inside of the sleeve *C* so that downward motion of the sleeve *C* with respect to the operating piston *B* brings the port *D* into communication with the port *E* in the operating piston, admitting oil above the operating piston in the chamber *F*, causing the operating piston to move downward until the port *E* cuts off communication with the port *D*, whereupon equilibrium is again established. A second recess *G* is provided in the relay sleeve *C* which communicates with the port *H* in the operating piston, and brings the space *F* into communication with the exhaust when the relay sleeve *C* moves upwards relative to the operating piston *B*.

From the mode of operation of the relay device shown in Fig. 21, it is obvious that the relay sleeve *C* moves only a small distance relative to the operating piston *B*. Now, if the relay sleeve *C* were of 10 square inch area, as the piston in Fig. 15, and the total travel

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of the operating piston were two inches, the load and scale of the spring required to hold the relay sleeve in position would be the same as in the case of Fig. 20, and as we saw, this necessitated a spring capable of carrying a total load of 1000 pounds and having a scale of 40 pounds, requiring an initial stretch of 25 inches.

As the inside diameter of the relay sleeve would be approximately three inches and about one-eighth inch clearance would be required around the spring, the spring could not be over 2.75 inches diameter. Now, assuming a stress of 66 000 pounds per square inch, in the spring, the proportions would be as follows:—2.25 in. mean diameter of coil, 7/16 in. diameter wire, 112 coils. This spring would have a scale of 40 pounds per inch, and would have a length of 48.25 in. close wound, and a length of 73.25 in. when given an initial stretch of 25 in. to carry the 1000 pound load. It is obvious that a spring over six feet long would be entirely impracticable.

Since the relay sleeve always returns to a neutral position with reference to the operating piston and only a very slight motion of not over 1/16 inches is required to open the ports, and the total variation of load on the spring is only approximately 80 pounds, the thought naturally occurs that if say 900 pounds of the total of 1000 pounds could be carried by a spring which only had to have 1/16 inch travel, it would be very easy to design a small spring with 40 pounds scale to carry the remaining 100 pound load.

This is what has been done in Fig. 22. If, in place of a single spring, two springs are employed, the heavy external spring, or load spring, as it has been called, is

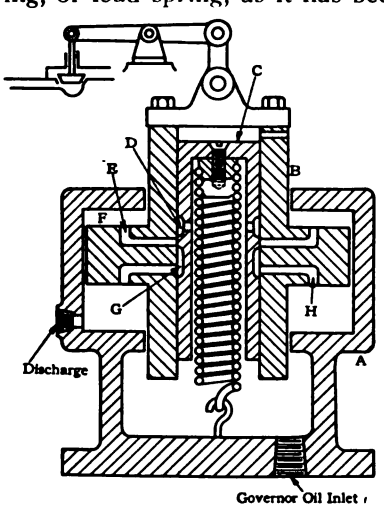


FIG. 21—A SIMPLE SINGLE-SPRING OIL RELAY

attached at its upper end to the relay sleeve shackle nut and at its lower end to a shackle nut carried by the operating piston trunk, so that the load spring travels with the operating piston and the only extension required of it is just sufficient to uncover the ports, or a total travel in a double-acting piston of 1/8 inch, or 1/16 inch in a single-acting piston. The load spring would carry approximately 800 pounds load and have a motion of 1/8 inch for four percent speed variation, or 80 pounds change of load. The scale of this spring would consequently be 80 divided by 1/8 or 640 pounds per inch; i.e., sixteen times as stiff as the spring required for Fig. 21, or instead of a length of something over 74 inches, the length required would only be 4-5/8 inches.

The small inner spring, termed the scale spring, would carry a load of 200 pounds and have a scale of 40 pounds. Such a spring designed with a relatively low stress of 48 000 pounds (to allow for extra load due to overspeed tests,) would have a 1.5 inch diame-

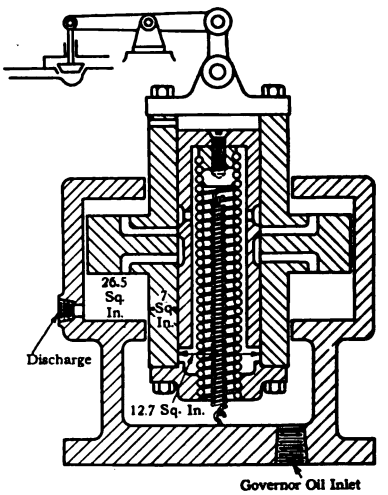


FIG. 22—A SIMPLE TWO-SPRING OIL RELAY

ter, 1/4 inch wire and 40 turns, giving a close wound length of 10 inches and an extended length of 15 inches, which easily works into the design of a relay of this size.

The action of the relay mechanism in Fig. 22 is the same as that in Fig. 21, the difference being in the spring arrangement. It will be noted that, as in Fig. 21, the operating piston is made single acting. The reason for this is that the oil pressure acting on the relay sleeve and the annular area of the operating piston trunk gives an upward force of approximately 2000 pounds. The annular area of the operating piston is made approximately equal to twice the area of the relay sleeve and trunk, so that the operating force is approximately equal in both directions, though the piston is made single acting.

The speed at which this relay governs is varied by increasing or decreasing the tension of the load spring. In Fig. 23, this is accomplished by the worm *A* and wheel *B* keyed to the sliding sleeve *C*, which latter is threaded and engages the lower shackle nut.

In the relay arrangement shown in Fig. 23, the difficulty of an impracticable spring length was obviated by the use of two springs, the load spring travelling with the operating piston. If it were possible to permit the end of the load spring to travel with the operating cylinder, but at a slightly smaller rate of advance, the effect of a longer spring with weak scale could be obtained, although the actual scale of the spring were very large. This is carried out in Fig. 24, which shows a form of relay used in many turbines. The upper end of the operating piston is connected to a lever *A* ful-

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crumed on a roller *B*, and is connected to a second lever *C* by the link *D*. The lever *C* is fulcrumed in the housing and carries the shackle nut *E*, to which the lower nut of the relay spring is attached. The arms of the levers *A* and *C* are so proportioned that the shackle nut *E* does not advance quite as rapidly as the operating piston, so that the relay spring is stretched slightly as the operating piston travels from the bottom to the top of its stroke. These lever arms can be so arranged that, as the operating piston moves two inches the shackle nut *E* moves 1.8 in., giving a stretch to the spring of 0.2 in. or ten percent of the travel. Thus, taking the example of Figs. 21, 22, the spring would have a scale of 80 divided by 0.2 or 400 lb. per in., which gives a reasonable spring, easily fitted within the length of an ordinary relay mechanism. While the actual scale of the spring would be 400 lb., its effective scale is still only 40 lb., since, in traveling from the lower to the upper limit of its movement, the stretch is only 0.2 in., which gives a change of load on the relay valve sleeve of 400 × 0.2, or 80 lb., corresponding to a speed variation of four percent.

A valuable feature in Fig. 22 and 23 is that there is no linkage between the relay valve, which admits fluid to the operating cylinder and the governor piston, since the relay valve sleeve also acts as the governor piston. In other words, the relay valve has its own governing force and has nothing to move but itself. The apparent advantages of this arrangement have been borne out in practice by the remarkable sensitiveness of these mechanisms to changes in the oil pressure, pressure changes much too small to be read on an ordinary pressure gauge being sufficient to operate the relay. In Fig. 24, all the various links and levers are constructed with plain pin bearings with no special provision for lubrication, since the power for moving all this linkage is provided by the operating piston and the power required to move this mechanism due to friction or sticking does not in any way affect the sensitiveness and operation of the relay valve sleeve.

It will be obvious that any desired speed variation can be obtained with the same spring by varying the ratio of the levers, *A* and *C*. This makes possible the arrangement shown in Fig. 24, in which, by the use of the cam, *F*, which is held from sliding along the lever *A* by the link *G*, attached to part of the housing, the lever ratio is varied with the travel of the operating piston in such a manner that a common poppet valve can be made to have the same steam characteristics as the ported valves generally used in governor controlled valves. By properly forming the cam, *F*, the travel of the operating piston for a given change of load can be varied in such a manner that equal increments of steam flow will be secured with equal increments of oil pressure change and hence, speed change. In other words, the travel will be directly proportional to the load up to the point where the steam reaches the critical velocity through the valves, beyond which the valve opening is caused to increase more rapidly to compensate for the decreased flow per unit of area through the valve.

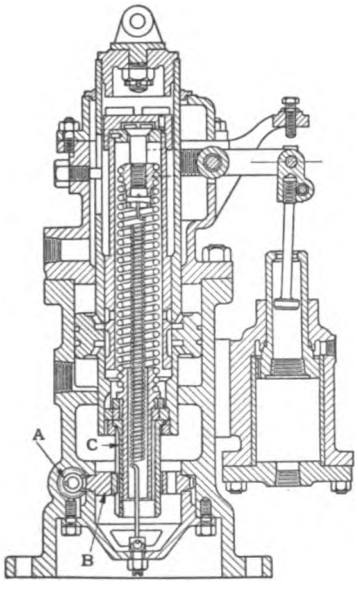


FIG. 23—A MARINE TYPE TWO-SPRING OIL RELAY

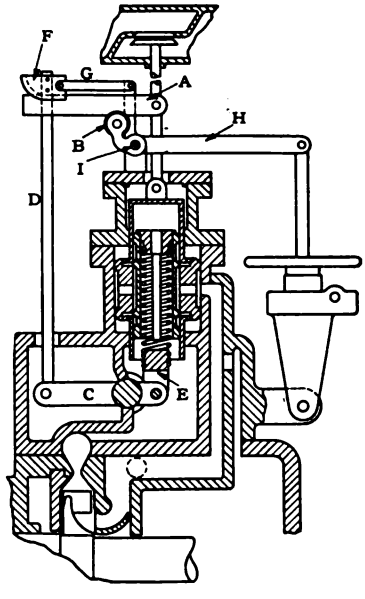


FIG. 24—THE EFFECT OF THE RELAY IN FIG. 23 OBTAINED WITH A SMALLER SPRING

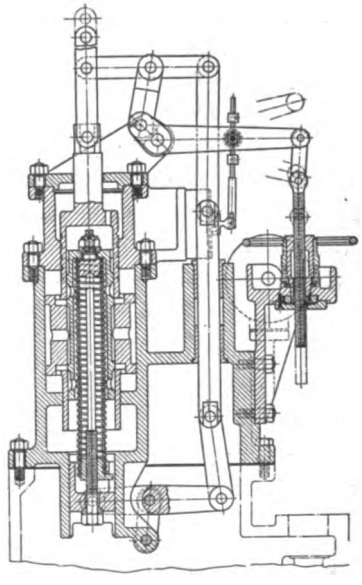

FIG. 25—A MORE DETAILED SKETCH OF THE RELAY SHOWN DIAGRAMMATICALLY IN FIG. 24

To alter the speed variation of this governor permanently, the governor spring is either shortened or lengthened by screwing up on the spring shackle nuts. The speed changer for synchronizing operates through the lever *H*, which is fulcrumed at *I* and carries the roller pivot *B*. The motion of the lever *H* moves the fulcrum *B* up or down, stretching or shortening the governor spring, thus changing the speed at which the relay operates.

A centrifugal pump running at a given speed creates a certain difference of pressure between the inlet and discharge. Consequently, the total pressure delivered by the pump will be the sum of the pressure at the suction plus the pressure created by the pump.

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Since, for governing purposes, it is very desirable to supply the oil to the governor under a positive head of five to ten pounds to avoid the danger of the pressure falling below atmospheric upon sudden demand by the operating cylinder, thus causing air to be drawn in which would interfere with the operation of the governor, the ejectors supplying oil to the impeller are designed to give about five to ten pounds. The pressure delivered by the ejecter, however, varies somewhat with the temperature and viscosity of the oil and also with the demand. Consequently, since the suction pressure varies, possibly as much as 1 or 2 pounds under some conditions, this variation of pressure would appear at the discharge and interfere with governing.

To obviate this, an arrangement similar to that shown diagramatically in Fig. 26 is employed. The impeller delivers oil to the ejector, which in turn delivers oil to the suction of the impeller. A connection from the suction of the impeller is carried to the low pressure side of the governing piston or to the top of the relay valve sleeve. In this way, both sides of the operating piston or relay valve sleeve are subjected to the same fluctuations of pressure due to variations at the inlet to the pump, and thus the operation of the relay mechanism, or governor piston in the direct acting governor, is made independent of any fluctuations in the delivery pressure from the ejector.

As a matter of fact, while this provision can be made and has been made in some designs, if the ejector is of sufficient capacity, the variations of pressure are so slight that they do not seriously interfere with the governor, and many of the smaller turbines equipped

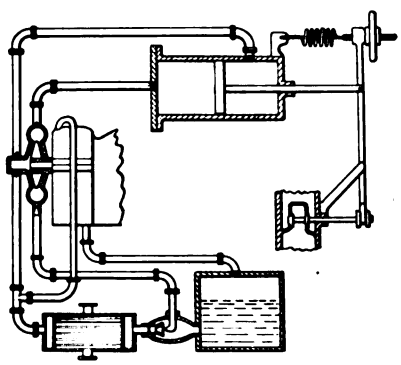

FIG. 26—OIL GOVERNOR BALANCE FOR IMPELLER INLET PRESSURE

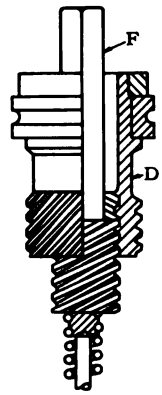


FIG. 27—THE DIFFERENTIAL THREAD IN DETAIL

with oil governors have not been provided with this connection. From the foregoing examples of relay mechanisms, it is seen that the difficulty encountered in the design of a suitable spring can be obviated by imparting a differential motion to the ends of the spring.

A different design of differential motion can be obtained by the use of two screws and nuts having slightly different pitches one working within the other. The operating piston and relay valve sleeve are the same and function the same as in the preceding example. In Fig. 28, the operating liner *A*, is feather keyed to the operating piston *B* the upper trunk of which is internally threaded at *C* and engages an externally and an internally threaded member *D* free to rotate on ball bearings *E*. The externally and internally threaded member *D* engages the central threaded spindle *F* to which the governor spring is attached. The spindle *F* is splined or made with a square end *G* which engages the housing cover *H*, which prevents it from rotating. The external thread of the member *D* is of slightly greater pitch than the internal thread, and both threads

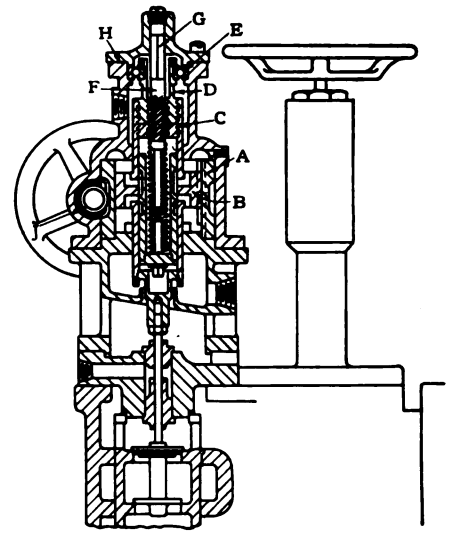


FIG. 28—OIL RELAY DIFFERENTIAL THREAD ARRANGEMENT

are of sufficient pitch that the parts can be forced to rotate by pushing any of the members longitudinally with respect to the other members. If, therefore, the operating piston *B* and its threaded trunk moved upward sufficiently to rotate the member *D* one revolution, the member *G* would move upwards an amount equal to the motion of operating piston *B*, but would move downwards an amount equal to the difference of pitch of the inner thread in one revolution. In other words, the spindle *F* would move upwards an amount equal to the difference in the pitches of the internal and external threads of the member *D* for one revolution. Thus, the spindle *F* would move upwards but not quite as far as the operating piston *B*.

The adjustment for changing the speed is made by means of the worm *J*, which engages teeth cut in the outer periphery of the operating cylinder liner *A*. When *A* is rotated, it screws the trunk of the operating piston along the member *D*, causing the spindle *F* to be moved relative to the operating piston and relay valve sleeve, thus either increasing or decreasing the tension of the spring. If it is desired to change the speed variation of the governor, this is accomplished in the usual way, either by cutting off coils from the spring or screwing the spring farther on to the spring shackle nuts, as is customary in other types of governors.

Here, again, it is seen that the relay valve sleeve is perfectly free to move under changes of pressure of the governing oil, the power required for driving the screw differential motion being furnished by the operating piston. The details of the member *D* and stem *F* are shown in Fig. 27.

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# Symmetrical Components

## III—Calculation of Unbalanced Faults

C. F. WAGNER and R. D. EVANS

In the preceding articles the fundamentals of the method of symmetrical components were developed and discussed. Provided only that the impedances of the three phases be symmetrical, i.e. that, viewed from any phase, both the self and mutual impedances are respectively equal, it was shown for any impedance group containing either self or mutual impedances or both that the three sequences of current or voltage may be considered independently—they do not react one upon the other. Such a system contains only the three impedances of zero sequence. A current of a particular phase sequence gives rise to a voltage of the same sequence only. The ratio of this voltage to the current for any phase sequence is termed the impedance of the circuit to that phase sequence. This relation applies not only to static networks, but to rotating machines as well. A succeeding article will be devoted to the determination of the impedance of different types of circuits and machines to the flow of current of the different sequences. A knowledge of these constants is a prerequisite to the calculation of unbalanced faults. For the present it will be assumed that these constants are known, and methods will be developed for the calculation of system faults. Two general cases will be considered: (1) those systems in which resistance and capacity may be neglected and only reactances taken into account, (2) the more general case in which resistance, charging current, etc., are taken into consideration. Both of these cases will be demonstrated by examples.

### KIRCHHOFF'S FIRST LAW

The analysis so far pertains to but one branch. The voltage drops of the various sequences are dependent only upon the current and the impedance of the same sequence. What will be the result when a group or network is considered? At each junction, e.g., the junction in Fig. 12 in which four circuits converge, by Kirchhoff's Law the sum of currents in all the conductors equals zero:

$$\left.\begin{aligned} I_a' + I_a'' + I_a''' + I_a'''' &= 0 \\ I_b' + I_b'' + I_b''' + I_b'''' &= 0 \\ I_c' + I_c'' + I_c''' + I_c'''' &= 0 \end{aligned}\right\} \quad \text{.....(89)}$$

or expressed in terms of the sequence operator

$$S(I_a') + S(I_a'') + S(I_a''') + S(I_a'''') = S(0) \quad \text{.....(90)}$$

Expanded this becomes:

$$\begin{aligned} &S^0(I_{a0}' + I_{a0}'' + I_{a0}''' + I_{a0}'''') \\ &\quad + S^1(I_{a1}' + I_{a1}'' + I_{a1}''' + I_{a1}'''') \\ &\quad + S^2(I_{a2}' + I_{a2}'' + I_{a2}''' + I_{a2}'''') \\ &\quad = S^0(0) + S^1(0) + S^2(0) \end{aligned}$$

From which

$$\left.\begin{aligned} S^0(I_{a0}' + I_{a0}'' + I_{a0}''' + I_{a0}'''') &= S^0(0) \\ S^1(I_{a1}' + I_{a1}'' + I_{a1}''' + I_{a1}'''') &= S^1(0) \\ S^2(I_{a2}' + I_{a2}'' + I_{a2}''' + I_{a2}'''') &= S^2(0) \end{aligned}\right\} \quad \text{.....(91)}$$

and

$$\left.\begin{aligned} I_{a0}' + I_{a0}'' + I_{a0}''' + I_{a0}'''' &= 0 \\ I_{a1}' + I_{a1}'' + I_{a1}''' + I_{a1}'''' &= 0 \\ I_{a2}' + I_{a2}'' + I_{a2}''' + I_{a2}'''' &= 0 \end{aligned}\right\} \quad \text{.....(92)}$$

These equations show that the various sequence components at any junction must individually add up to zero; each sequence of currents obey Kirchhoff's first law separately. This proof has been given for four circuits, but it is apparent that it is a perfectly general relation which must always hold at any junction and may be extended to any number of conductors.

### KIRCHHOFF'S SECOND LAW

Consider a general network of lumped constants, either self or mutual impedances. Since the voltage drops of each phase sequence may be considered separately, the sum of the voltage drops of any sequence around any closed circuit must be equal to the e.m.f.'s of that same sequence. In this respect the network phenomena obey Kirchhoff's second law. This holds true for all points in the system, including the point of fault if this point be considered as a source of zero, negative and positive sequence voltage, $\check{e}_0$, $\check{e}_2$, and $\check{e}_1$,

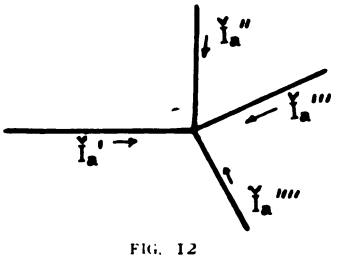


FIG. 12

respectively. So, the system may be considered as three separate and distinct networks; one for positive sequence, one for negative sequence and the third for zero sequence. The tie between these systems will be the terminal conditions at the point of fault.

Consider these networks individually. The positive sequence network is in all respects similar to the usual networks considered; the resistances and reactances are the values usually given to calculate line regulation. Each synchronous machine must be considered as a source of e.m.f. which may vary in magnitude and phase position, depending upon the distribution of real and reactive power just previous to the application of the fault. At the point of fault the positive sequence voltage $\check{e}_1$ will drop, the amount being conditioned upon the type of fault; for three-phase faults it will be zero; for double faults to ground, line to line faults and single-phase faults to ground, it will be higher in the order stated. The exact value is calculable and will be determined.

The negative phase sequence network is in general quite similar to the positive sequence network.

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Because positive sequence voltages only are generated in the synchronous machines, this network will contain no sources of e.m.f. except the fictitious one at the point of fault.

The zero phase sequence network will likewise be free of internal voltages, the flow of current resulting from the voltage at the point of fault. The impedances to this sequence are radically different from those of either the positive or negative sequences. The line impedances are those obtained by imagining the three conductors connected together, the ground forming the return conductor. The transformer and generator impedances will depend upon the type of connection, whether delta or star connected, if star whether grounded or not. The calculation of the impedances to negative and zero phase sequences will be considered in a subsequent article. For the time being, let it be assumed that these quantities are given.

In particular consider the system shown in Fig. 13 (a). Two generators *A* and *B* at the sending end of a line are connected to two delta-star transformers (only one of which is grounded) which are bussed on the high side. At the receiving end there are two star-star transformer banks (both grounded on high side, but only one on low side) connected to separate generators. The load is assumed concentrated at the receiving end and is partially supplied by the local generators *C* and *D*, one of which is grounded.*

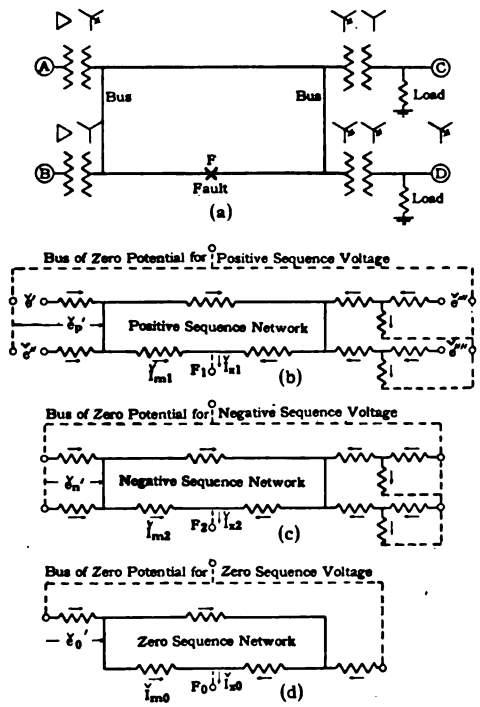


FIG. 13—DIAGRAMATIC REPRESENTATION OF THE THREE SEQUENCE NETWORKS FOR A THREE-PHASE ELECTRICAL SYSTEM

Assume the fault to occur at the point *F* midway on one of the lines. The single line impedance diagram for the positive sequence is shown in Fig. 13 (b), and that for the negative and zero sequence in Fig. 13 (c) and (d). The synthesis of these respective networks will be discussed later. Let it suffice for the time being to point out that the impedances of the various branches for the different sequences are represented by the impedances in the corresponding topographical position. It is important to retain the positive flow of current, as indicated by the arrows, the same in any branch for all three networks, as the fundamental equations postulate this condition. $\check{e}'$, $\check{e}''$, $\check{e}'''$, and $\check{e}''''$ are the internal voltages of the four generators *A*, *B*, *C*, and *D* respectively. Since positive sequence voltages, only, are generated within the machines, the corresponding internal voltages for the negative and zero sequence networks are zero and, being of the same potential, these points may be connected together as shown by the dotted lines. Now the only tie between these otherwise independent networks is the terminal conditions at the point of fault. The nature of this tie will vary with the character of the fault. Four cases will be considered in this analysis:

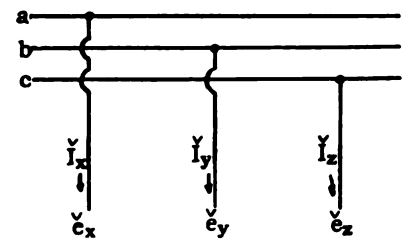


FIG. 14

1—Ground fault on one conductor.
2—Double fault to ground.
3—Single-phase line to line fault.
4—Three-phase fault.

Imagine three short conductors of zero impedance connected to the three line conductors at the point of fault. The terminal conditions imposed by the different types of faults will be applied to these imaginary leads, the potentials to ground of which will be $\check{e}_x$, $\check{e}_y$, and $\check{e}_z$ respectively, and the currents $I_x$, $I_y$, and $I_z$. These imaginary conductors are shown in Fig. 14.

1—*Ground Fault on One Conductor*—For this case suppose the *a* phase to be grounded as indicated in Fig. 15 (a). The terminal conditions in this case are:

$$\left.\begin{aligned}\check{e}_x &= 0\\ I_y &= 0\\ I_z &= 0\end{aligned}\right\} \quad \ldots\ldots(93)$$

From equations (30), (31) and (32) of the first article the symmetrical components of current are:

$$I_{x0} = 1/3\,(I_x + I_y + I_z) = 1/3\,(I_x) \quad \ldots\ldots(94)$$
$$I_{x1} = 1/3\,(I_x + a I_y + a^2 I_z) = 1/3\,(I_x) \quad \ldots\ldots(95)$$
$$I_{x2} = 1/3\,(I_x + a^2 I_y + a I_z) = 1/3\,(I_x) \quad \ldots\ldots(96)$$
$$\text{or } I_{x0} = I_{x2} = I_{x1} \quad \ldots\ldots(97)$$

Also

$$\check{e}_x = \check{e}_{x0} + \check{e}_{x1} + \check{e}_{x2} = 0 \quad \ldots\ldots(98)$$

Now from equation (97) it can be seen that the currents at $F_1$, $F_2$, and $F_0$, Fig. 13, in the three networks for the three sequences are equal, and if the point $F_1$ of the positive sequence network be connected to the bus of zero potential in the negative sequence network, and the point $F_2$ in the negative sequence net-

*The unusual connections shown in this diagram are used merely to illustrate the method as applied to different transformer connections.

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work be connected to the bus of zero potential in the zero sequence network, as shown in Fig. 15, the three networks will be connected in series and the same total current must flow through the three networks. Since the current distribution within each of the networks is determined solely by the impedances in the indi-

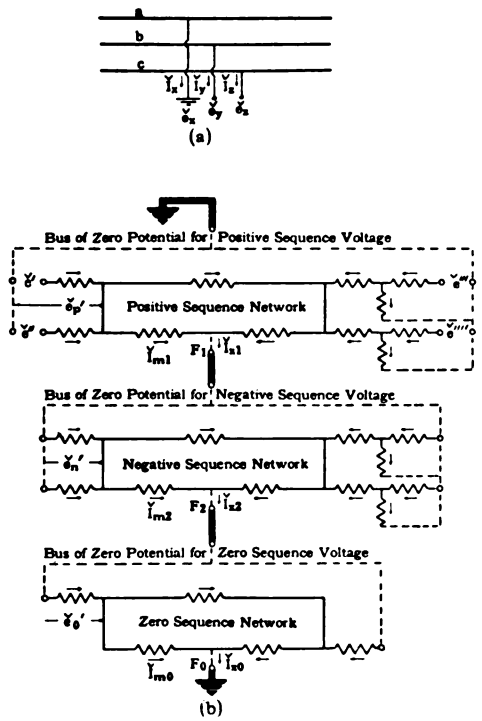


FIG. 15—THE THREE SEQUENCE NETWORKS FOR A GROUND FAULT ON ONE CONDUCTOR

vidual networks, this combination of the networks enables one to determine the current distribution in any branch. However, for this connection to determine the current completely the relation expressed in equation (98) must also be satisfied.

Now starting from any one of the internal voltages of Fig. 15, say $\check{e}'$, and tracing one's way through the network by any path to $F$, it can be seen that the positive sequence voltage $\check{e}_1$ at $F$ is equal to

$$\check{e}' - \Sigma \text{ positive sequence voltage drops from } \check{e}' \text{ to the point } F \quad (99)$$

Similarly with the negative sequence network, starting at any point of zero potential within one of the machines and tracing one's way to $F$ it will be found that

$$\check{e}_2 = 0 - \Sigma \text{ voltage drops to the point } F \quad (100)$$

and for the zero sequence network

$$\check{e}_0 = 0 - \Sigma \text{ voltage drops to the point } F \quad (101)$$

Adding these three voltages and equating to zero as indicated by equation (98):

$$0 = \check{e}' - \Sigma \text{ voltage drops from } e' \text{ to } F \text{ in pos. seq. network} - \Sigma \text{ voltage drops from machines to } F \text{ in neg. seq. network} - \Sigma \text{ voltage drop from machines to } F \text{ in zero seq. network} \quad (102)$$

or

$$\check{e}' = \Sigma \text{ voltage drops from } e' \text{ to } F \text{ in pos. seq. network} + \Sigma \text{ voltage drops from machines to } F \text{ in neg. seq. network} + \Sigma \text{ voltage drops from machines to } F \text{ in zero seq. network} \quad (103)$$

If the potential of $F_0$ be made equal to zero, i.e., the neutral of the balanced system, it can be seen that equation (103), and consequently also equation (98) will be satisfied, and the connection of Fig. 15 will completely determine the flow of current. The positive, negative, and zero sequence currents in any branch are equal to the actual currents flowing in the respective branches in the three networks.

The determination of the sequence and phase voltages and currents at any point in the system will be discussed in connection with the application of the calculating board. This will insure a better picture of the correlation of the different networks and provide a better conception of the physical significance of the various quantities.

2—*Double Fault to Ground*—For this case assume both phases $b$ and $c$ faulted to ground simultaneously as shown in Fig. 16 (a). The terminal conditions for this case are then

$$\left.\begin{aligned} \check{e}_y &= 0 \\ \check{e}_z &= 0 \\ \check{I}_x &= 0 \end{aligned}\right\} \quad (104)$$

From equations derived in the first article of this series*

$$\left.\begin{aligned} \check{e}_{x0} &= 1/3\,(\check{e}_x + \check{e}_y + \check{e}_z) = 1/3\,(\check{e}_x) \\ \check{e}_{x1} &= 1/3\,(\check{e}_x + a\,\check{e}_y + a^2\,\check{e}_z) = 1/3\,(\check{e}_x) \\ \check{e}_{x2} &= 1/3\,(\check{e}_x + a^2\,\check{e}_y + a\,\check{e}_z) = 1/3\,(\check{e}_x) \end{aligned}\right\} \quad (105)$$

or

$$\check{e}_{x0} = \check{e}_{x1} = \check{e}_{x2} \quad (106)$$

Also

$$\check{I}_x = \check{I}_{x0} + \check{I}_{x1} + \check{I}_{x2} = 0 \quad (107)$$

Equations (106) and (107) define the conditions

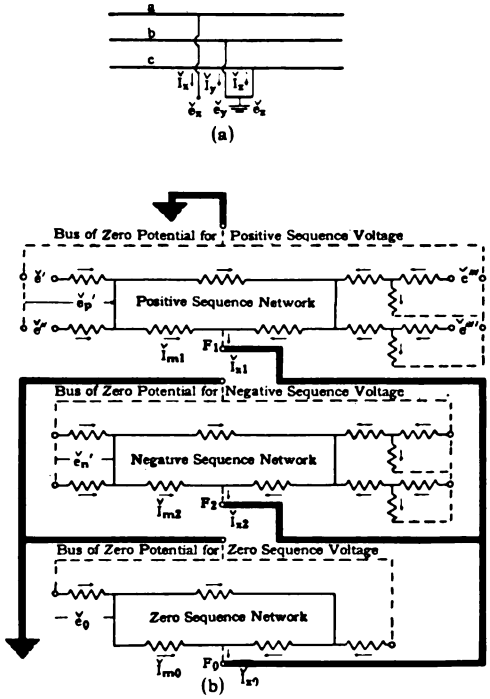


FIG. 16—THE THREE SEQUENCE NETWORKS FOR A DOUBLE FAULT TO GROUND

which must be fulfilled at the terminals for this case.

Connecting the three networks of Fig. 13 as shown in Fig. 16 it will be seen that the two above conditions

*In the JOURNAL for March 1928, p. 151.

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are fulfilled; equation (107) is fulfilled at the junction of the three networks and equation (106) is fulfilled because the three voltages are measured across the same terminals and must therefore be equal to each other.

3—*Single-Phase Line-to-Line Fault*—Assume the fault to occur between phases *b* and *c*. The terminal conditions for Fig. 17 (a) are then

$$\left.\begin{aligned} I_x &= 0 \\ I_y &= -I_z \\ \check{e}_y &= \check{e}_z \end{aligned}\right\} \quad \ldots\ldots(108)$$

The sequence components are then

$$I_{x0} = 1/3\,(I_x + I_y + I_z) = 1/3\,(0 - I_z + I_z) = 0 \quad \ldots\ldots(109)$$

$$I_{x1} = 1/3\,(I_x + aI_y + a^2 I_z) = 1/3\,(0 - aI_z + a^2 I_z) = \frac{-a + a^2}{3} I_z \quad \ldots\ldots(110)$$

$$I_{x2} = 1/3\,(I_x + a^2 I_y + a I_z) = 1/3\,(0 - a^2 I_z + a I_z) = \frac{+a - a^2}{3} I_z = -I_{x1} \quad \ldots\ldots(111)$$

Since $I_{xo} = 0$ it follows that $\check{e}_{xo}$ must also be equal to zero. Furthermore, since

$$\left.\begin{aligned} \text{since} \quad \check{e}_{x1} &= \check{e}_x + a\,\check{e}_y + a^2\,\check{e}_z \\ \text{and} \quad \check{e}_{x2} &= \check{e}_x + a^2\,\check{e}_y + a\,\check{e}_z \end{aligned}\right\} \quad \ldots\ldots(112)$$

Then, substituting in these equations the relations:

$$\check{e}_y = \check{e}_z$$

and

$$\check{e}_{x0} = 0$$

$$\check{e}_{x1} = (a + a^2)\,\check{e}_z \quad \ldots\ldots(113)$$

$$\check{e}_{x2} = (a + a^2)\,\check{e}_z \quad \ldots\ldots(114)$$

$$= \check{e}_{x1} \quad \ldots\ldots(115)$$

Because both $I_{xo}$ and $\check{e}_{xo}$ are zero, the zero sequence network can be eliminated from consideration. The only conditions which must be fulfilled by the

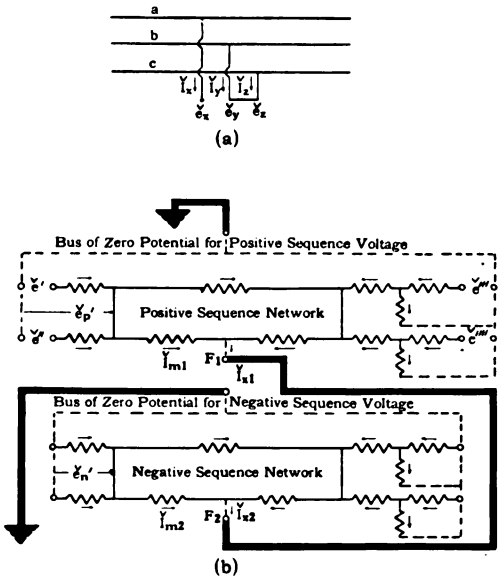


FIG. 17—THE THREE SEQUENCE NETWORKS FOR A SINGLE-PHASE LINE TO LINE FAULT

equivalent network are those expressed by equations (111) and (115). By connecting the positive and negative sequence networks as shown in Fig. 17 it may be seen immediately that equation (111) is satisfied because $I_{x1}$ must always equal $-I_{x2}$. Equation (115) is satisfied because the equal voltages expressed thereby are measured from the same point and hence must be equal.

4—*Three-Phase Faults*—This case is the simplest and the one most familiar to persons calculating short-circuits for the application of circuit breakers and relays. The equivalent diagram reduces to that shown in Fig. 18. Since the system remains balanced, the negative and zero sequence networks do not enter the problem.

APPLICATION TO CALCULATING BOARDS

The calculation of system faults by the methods just described may be greatly facilitated by the use of calculating boards. By means of an alternating-cur-

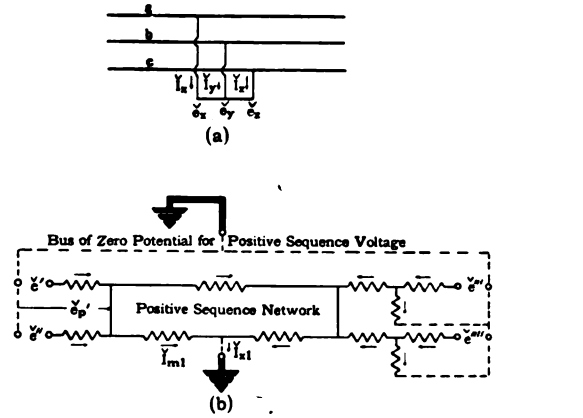


FIG. 18—THE THREE SEQUENCE NETWORKS FOR A THREE-PHASE SHORT-CIRCUIT

rent board with resistors and reactors and several sources of e.m.f., the three complete sequence networks representing the characteristics of the actual system may be set up simultaneously. By appropriate connection of these networks, in the manner just described, the different kinds of faults can be represented. Regardless of the manner in which the sequence networks are connected, the current in phase *a* at any point can always be obtained by adding the currents of the three networks at the corresponding points. Suppose it is desired to determine the current in the left hand section of the faulty line in Fig. 13. The current in phase *a* is determined by adding directly the current $I_{m1}$ from the positive-sequence network, $I_{m2}$ from the negative-sequence network, and $I_{m0}$ from the zero-sequence network. This can be accomplished most conveniently by plugging into the three networks by means of current transformers and totalizing on the secondaries. For phases *b* and *c*, networks can be devised which shift the positive and negative sequence components 120 and 240 degrees; the shifted currents can then be added to the zero sequence current. In the absence of such a device the phase currents can be obtained by adding the quantities analytically after operating, by the unit vectors *a* and $a^2$, using the relations:

$$I_b = I_{m0} + a^2 I_{m1} + a I_{m2}$$

$$I_c = I_{m0} + a I_{m1} + a^2 I_{m2}$$

The sequence voltage for any point in a network appears only in the corresponding sequence network, so that the manner in which the sequence voltages are measured is independent of the particular way in which the networks are connected together for the rep-

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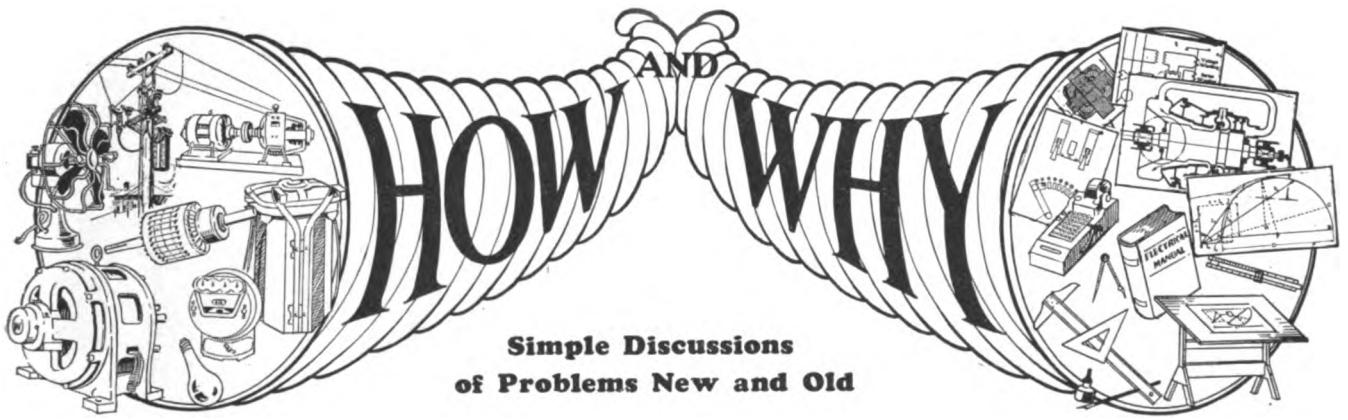
resentation of the different types of faults. In the positive sequence network the potential at any point is measured between that point and the point of zero or ground potential, indicated by the dotted line in the positive sequence network of Fig. 13. Expressed differently, it is equal to one of the generated e.m.f.'s minus the drop from the particular e.m.f. to the point considered. If the value of the particular e.m.f. be zero, the potential at the point will be the negative of the drop from the zero potential bus to the point. In the negative sequence network, since normally no generated e.m.f.'s of negative sequence exist, the negative sequence potential at any point will be merely the negative of the drop to the point from the bus of zero negative potential. Similar considerations apply to the zero sequence network, the potential at any point being the negative of the drop to the point from the bus of zero potential for the zero sequence network as indicated by dotted lines in Fig. 13. For example, the voltage of phase *a* on the left hand bus is equal to the vector sum of the voltages $\check{e}_p'$, $\check{e}_n'$, and $\check{e}_o'$, which are indicated in Fig. 13. Note that this voltage is equal to the generated positive sequence voltage $\check{e}''$ minus the drops in the generator and transformer due to the positive, negative and zero sequence currents. Thus it may be observed that at the internal voltage of the machine all the drops are zero and the voltage of phase *a* is the generated positive sequence voltage. Also, for the case of a single conductor fault to ground as the point under consideration approaches the fault point, the voltage of phase *a* approaches zero. On the alternating-current calculating board the phase *a* voltage can be obtained by direct addition by means of potential transformers, and the voltages of phases *b* and *c* by phase shifting devices or analytically by means of the fundamental relations connecting phase and sequence voltages.

For short-circuit studies in which only the magnitudes of currents are required it is usually permissible to assume that the generated e.m.f.'s are of the same magnitude and phase so that a single source may be used to represent the generated e.m.f. A further simplication results when it is found sufficiently accurate to assume all the impedances of the same phase angle. In this case the networks may be set up on a direct-current board, the elements of which are pure resistances.

When it is desired to obtain only the zero sequence currents or as they are sometimes called, residual or ground currents, the positive and negative sequence networks are required only for determining the magnitude of the fault current; the distribution of ground currents is determined of course only by the zero-sequence network.

Fault impedances may be introduced in the connections of the sequence networks for different types of faults and therefore, as will be shown in the next article, do not affect the method just described for measuring sequence and phase voltages and currents.

CORRECTION—In Fig. 5 p. 154 of the JOURNAL for March 1928 the letters $E_{b1}$ and $E_{c1}$ in the positive sequence diagram should be interchanged; and the letters $E_{b2}$ and $E_{c2}$ in the negative sequence diagram should be interchanged.




## Portable Inverted Synchronous Converters*

THE small machine in the foreground shaped like a nail keg is an inverted synchronous converter. The converter receives power at 115 volts direct-current and supplies 600 watts at 110 volts and 60 cycles alternating current to the rectifier at the left which rectifies the lower half of each wave and passes the power on to the magnetic hammer, one-half wave for each of the two magnets.

The portable inverted synchronous converter has been developed to meet the insistent demand in direct-current localities for small amounts of alternating-current power. Alternating current has been adopted as standard for many small devices, partly because of the greater prevalence of alternating current and partly because alternating current is superior in some cases. Small induction motors, because of their almost constant speed are used on electric phonographs. The new radio receiving sets, electrotherapeutic apparatus and some small tools use alternating current. Motor-generator sets could be and are used to produce the requisite alternating current, but the converter with its lower weight per kw of power supplied has a tremendous advantage when portability and low cost is desired.

*Based in part on an article by R. H. Chatto, of the Westinghouse Electric & Mfg. Co. in the *Southern Power Journal* for Jan., 1928.

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There are, however, several characteristics of a converter when running inverted which necessitates special design for successful, stable operation. An inverted converter has the surprising and unfortunate habit of increasing its speed when it is supplying power to inductive apparatus. The lagging current drawn from the converter creates an armature reaction which demagnetizes the fields. As the speed of a

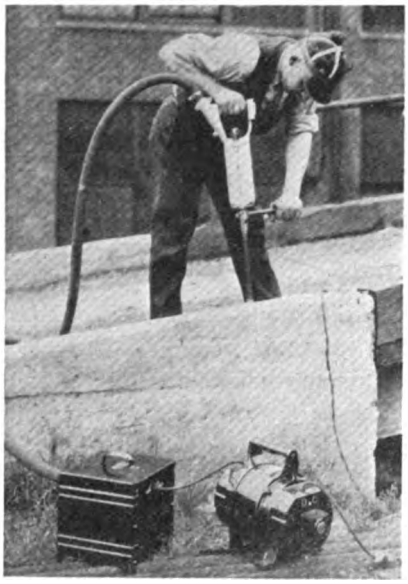

FIG. 1—A SMALL INVERTED SYNCHRONOUS CONVERTER PROVIDING POWER FOR A MAGNETIC HAMMER

direct-current motor—below field saturation—is inversely proportional to the field strength, inductive loads may produce disastrous speeds. To correct this, a cumulative series field is added which, as the load increases, strengthens the fields as much as the inductive loads weaken them.

The inverted converter can be designed to give practically constant frequency for any given power-factor load condition, as shown in Fig. 2 Curve *A*. However, at a load of any other power-factor the frequency will be different, as shown in Curve *B*. If this machine were loaded on an inductive load with power-factor below 65 percent, the frequency would rise with increasing load. It is apparent, therefore, that an inverted converter designed for a particular service may not be suitable to another service.

The inverted converter has been used but little in the past because, in its simplest form, the alternating-current voltage is considerably less than the direct-current voltage. In a single-phase converter the alternating-current voltage is but 70 per cent of the direct-current voltage. Thus, a converter operating from 115 volt direct-current lines would produce only 77 volts alternating current. But most alternating-current appliances require current at 110 to 115 volts. Thus some means must be provided to boost the alternating current output voltage. In order to obtain this voltage from a 110 volt direct-current circuit, a second winding is added to the armature. This winding is distributed over the armature slots and connected between one slip ring and the point where the ring would be connected to the armature winding. Where only 250 volt direct-current service is available, 110 volt alternating current can be obtained by reversing this booster winding.

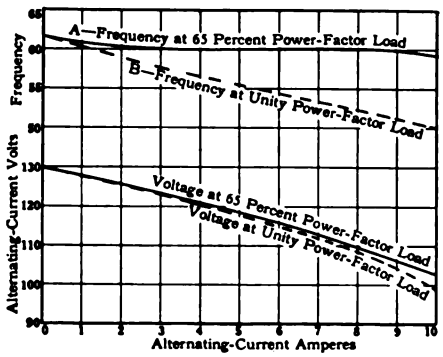


FIG. 2—CHARACTERISTICS OF AN INVERTED SYNCHRONOUS COVERTER

# Influence of Flux on Circuit-Breaker Top Design

F. BICE JOHNSON

THE tops of oil circuit breakers of various voltages and current ratings present a considerable variety of types of construction. Their design is influenced largely by four factors, whose relative influence in different cases determine the problem which the engineer must solve.

Two of these factors, the mechanical stresses to be met and the cost of construction are obvious. To meet the problems created by these two factors the use of iron or steel is immediately suggested. It is apparent, however, that if a magnetomotive force is present, flux will be introduced in the top. If the magnetomotive force is alternating, the flux will be alternating, in which case eddy currents will be induced in the top by the flux.

The current carrying loop of the alternating-current circuit breaker constitutes such a magneto-motive force. Therefore eddy currents may be expected in tops constructed of either iron or steel. Whether they are harmful depends on whether they are of sufficient magnitude to cause undue heating. Such heating becomes dangerous if the temperature of the metal around the terminal bushing becomes greater than

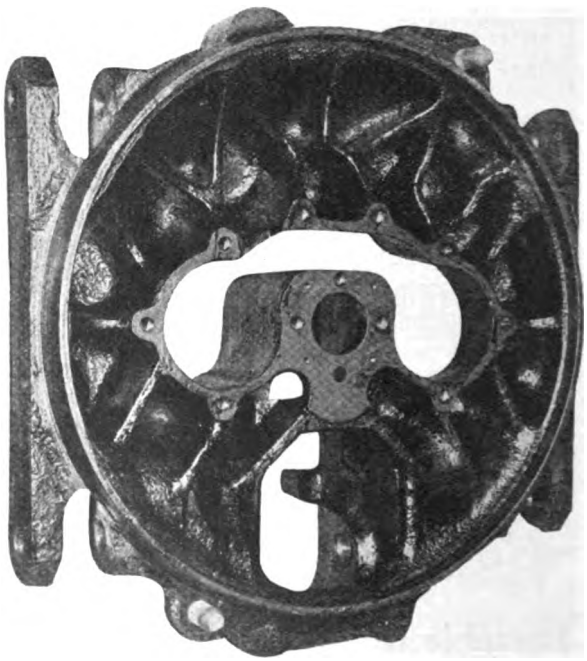

FIG. 1—A CIRCUIT-BREAKER TOP DESIGNED TO REDUCE FLUX

the allowable temperature at the circuit-breaker contacts. Under this condition, there is a possibility of heat being conducted from the top to the contacts which is an intolerable condition.

Practice shows that this undesirable condition will be obtained in certain cases if solid iron or steel tops are used. Heating is the third factor that muct be considered in designing the apparatus. The fourth arises from the necessity of weather-proofing circuit breakers for outdoor use.

Up to the present, the current carrying capacity of circuit breakers for 110 kv. and above has been comparatively low and the magnetomotive forces correspondingly low. Moreover the

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length of the magnetic path is greatly increased by the large bushing which insulates the current carrier from the case. Accordingly, the flux and eddy current conditions is a minimum in circuit breakers of this class. The flux problem in the design of these tops is usually slight. As a result the tops are constructed of rolled steel and are usually an integral part of the case. This practice leads to an economical construction which successfully handles the mechanical stresses present and is easily made moisture-proof.

In medium voltage circuit breakers with current carrying capacities of 600 amperes and lower, the eddy currents are not sufficiently high to cause trouble. These tops, being considerably smaller than those previously considered, are most economically constructed in the form of steel castings. This construction readily withstands the mechanical stresses and is easily made moisture-proof. In circuit breakers for higher currents, however, it becomes necessary to take steps to reduce the flux. Cast steel can be used for the tops of low voltage circuit breakers (15 to 25 kv) of the lowest current ratings, 600 amperes again being the maximum current with which the steel construction can be used.

Two methods of cutting down the flux are in general use. One consists in using a non-magnetic material, usually cast brass, for the top. The second consists of cutting out a section of the ordinary cast steel top between the terminal bushings and covering it with a brass cover. A picture of the underside of a cast steel top to which this has been done is shown in Fig. 1. When placed in use the section which has been cut out will be covered with a brass plate. This method has the disadvantages that it is not as effective in reducing the flux, it weakens the original casting, necessitating its reinforcement, and it is more difficult to weatherproof. It is somewhat cheaper than the cast brass construction, however, and is used for indoor circuit breakers of medium current carrying capacities. The cast brass construction is generally used for circuit breakers of current carrying capacities above about 2000 amperes and for all outdoor service where the flux conditions prohibit the use of cast steel.

## How to Prevent Transformer Oil Syphoning

HOW to prevent transformer oil from syphoning out along the leads has been a problem to engineers for years. At times it has reached the proportions of more than a nuisance, as lawsuits have occurred as the result of the syphoned oil dripping down on people's clothing. Besides this, there has been the expense of replacing the syphoned oil and the general unsightliness of oil on the ground or pavement around the transformer pole.

Syphoning results from the capillary attraction of liquids for surfaces close together. It can occur, for example, with a stranded cable in which oil may syphon along the lead between the stranded wires. It can also occur where insulation is wrapped around a lead, the oil finding its way upward between the layers of insulation.

The solution, clearly, is to eliminate the cause of the trouble, that is, to eliminate all enclosed surfaces along which the oil can creep. How to provide the necessary smooth, single surface has defied complete and practical solution for a long time. However, means have been devised which effectually solve the problem, as shown in Figs, 1, 2, 3 and 4.

When the voltage is low, below 1000 volts, and a solid conductor is used, the problem is safely solved by leaving the conductor bare as shown in Fig. 1.

In low-voltage transformers of larger current capacity, stranded leads are used. With only seven strands, oil syphoning through the strands is prevented by carefully soldering the strand a short distance above and below the oil level, as shown in Fig. 2, as in this case the soldier will completely fill the space between the wires.

When conductors of more than seven strands are used, soldering will not always prevent syphoning. The method shown in Fig. 3 is then applied. A seamless brass tube is

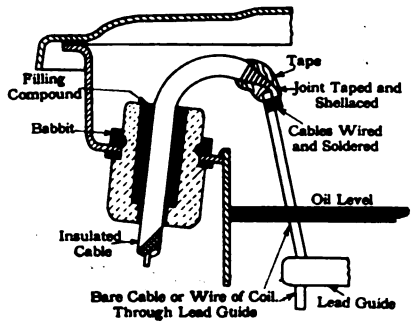


FIG. 1

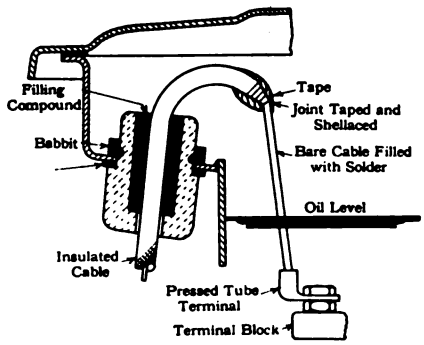


FIG. 2

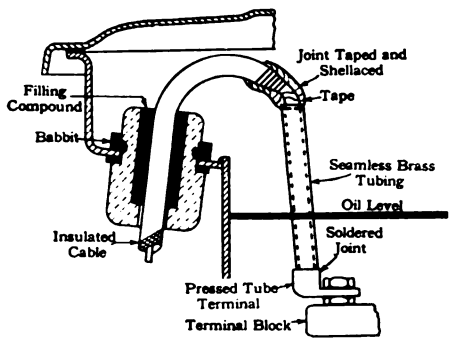


FIG. 3

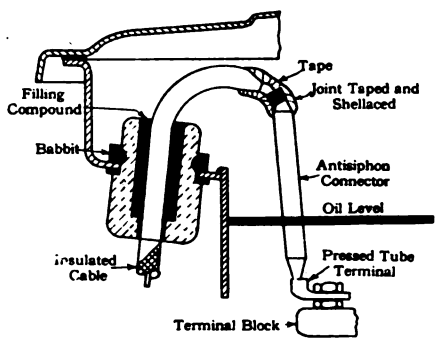


FIG. 4

slipped over the conductor and soldered to the terminal with the strand, thus providing the necessary smooth surface.

When the voltage is higher than 1000 volts, the conductor must be insulated. To do this and yet give a smooth exterior surface, a solid copper rod is soldered to the winding terminal and to the lead and then is tightly wrapped under heat and pressure with micarta. The arrangement is shown in Fig. 4.

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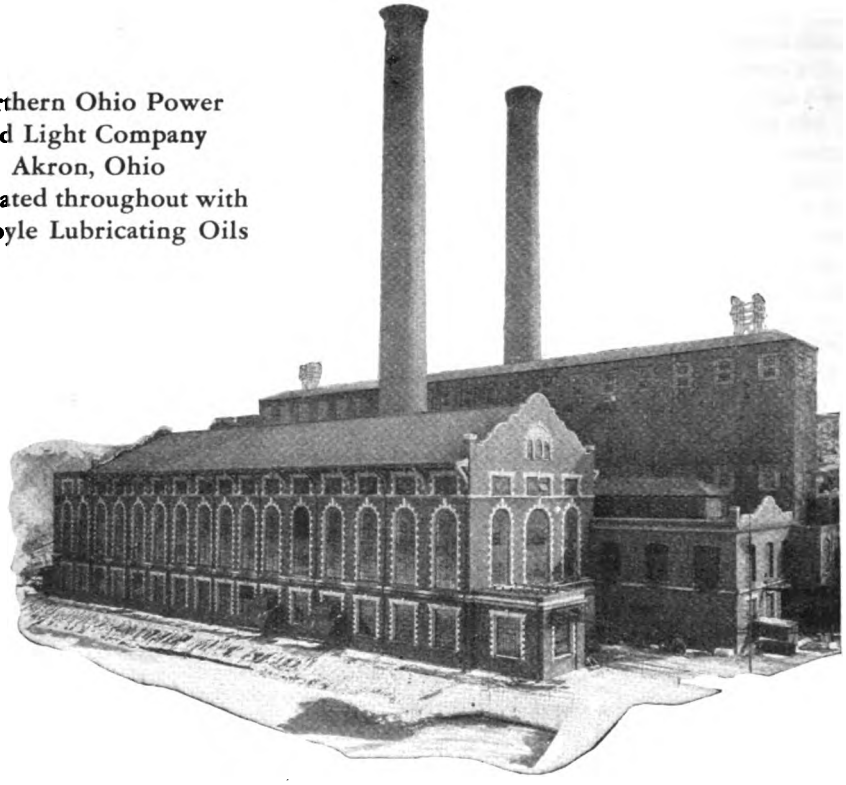

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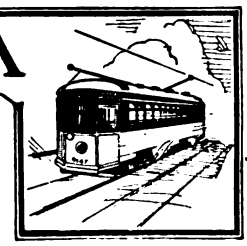
# RAILWAY OPERATING DATA

THE ELECTRIC JOURNAL

June 1928

The purpose of this section is to present accepted practical methods used by operating companies throughout the country.

The co-operation of all those interested in operating and maintaining railway equipment is invited. Address R. O. D. Editor



## Gear Center Distances on Railway Motors

THERE seems to be too little attention given to the proper maintenance of the gear center distances on railway motors. On the older types of motors using gears with 2½ to 3½ diametral pitch, this neglect is responsible for noisy cars and results in excessive vibration tending to break the gear teeth and to increase the cost of maintenance on the motors. With the modern, light-weight motors using gears that have smaller teeth, (diametral pitch from 4 to 4¼) a more serious trouble develops in that the teeth tend to get out of mesh, resulting in rapid wear and tear on the gears, and the equipment in general. In some instances this clearance has been so great as to permit the teeth to slip out of mesh, and both the gear and pinion are damaged beyond repair. In connection with this subject, the following points should be given some thought and action by railway operators.

TEN POINTS OF WEAR THAT AFFECT THE GEAR CENTER DISTANCE

1—*Housing fit to frame*[1]—When the frame is worn so that it will not clamp a new housing tightly enough to keep it from moving,—

a—Weld up the frame and bore the housing seat to standard size.

b—Rebore the frame at the housing seat to an oversize diameter, and use oversize housings.

2—*Frame fit on housing*[2]—When the outside diameter of the housing is worn so that the frame will not clamp it securely,—

a—Weld up and machine the housing to standard size. If the housing is made of cast steel, this can readily be done.

b—Machine to undersize and shrink on the housing a steel ring. Then machine the ring to standard size.

c—Use new through-bolt-type housings, having either standard or oversize outside diameter.

3—*Armature bearing fit in housing*—When the housing is worn so that a new bearing can be pressed in it with less than one ton pressure,—

a—Bore housing to oversize diameter and use oversize bearings.

b—Replace with new through bolt type housings and use standard size bearings.

c—Weld bore to standard size for standard bearings.

4—*Outside of armature bearing*[3]: When the outside of bearing shell is worn so that it is not a press fit in the housing,—

a—If made of bronze, expand the shell to standard size.

b—Copper plate the outside of the bearing shell.

c—Supply new bearings having standard outside diameter.

5—*Bore of Armature Bearing*[4]: The maximum allowable wear of bearings for motors under 50 hp in size should not exceed 1/32 inch. For motors 50 hp and over should not exceed 1/16 inch. When the wear exceeds these fixed limits,—

a—Rebabbitt shells and bore to standard size.

b—Replace with new standard size armature bearings.

6—*Shafts*[5]—Maximum allowable wear should not exceed 1/64 to 1/32 inch. When the wear exceeds these fixed limits,—

a—True up in a lathe and supply bearings with a smaller inside diameter to fit the reduced shaft size.

b—When wear is excessive shrink on a steel sleeve and machine to standard size.

c—Replace with a new shaft.

7—*Axles*[6]—Maximum variation in axle bearing seats should not exceed 1/32 inch. When the wear exceeds this limit if more than 3/32 in. undersize.

a—Turn down bearing seat of axle to uniform undersize diameter and use a smaller axle bearing machined to fit the axle. For most motors axle bearings in ¼ in. size are available.

b—Replace with a new standard size axle, if diameter bearing seat when turned down, exceeds the maximum permissible undersize for safe operation.

8—*Bore of Axle Bearing*[7]: Maximum allowable wear of bearings for motors under 50 hp should not exceed 1/8 inch. Motors 50 hp and over should not exceed 1/4 inch. When the wear exceeds these fixed limits,—

a—Rebabbitt bearing shells and machine to fit the axle.

b—Replace with new standard size axle bearings.

9—*Outside of Axle Bearing*—When the correct axle cap will not clamp the bearing tightly,—

a—Copper plate the outside of the bearing shell.

Involute Spur Gears—4¼ In. Diametral Pitch

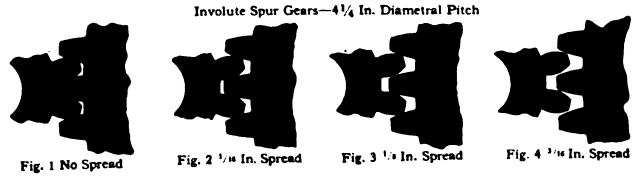


Fig. 1 No Spread — Fig. 2 1/16 In. Spread — Fig. 3 1/8 In. Spread — Fig. 4 3/16 In. Spread

Involute Spur Gears—3 In. Diametral Pitch

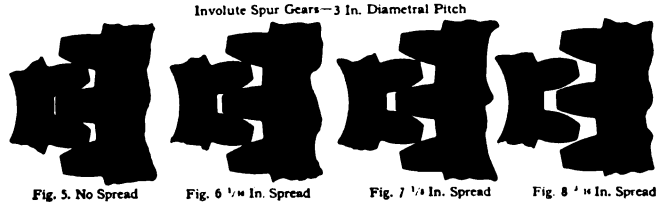


Fig. 5. No Spread — Fig. 6 1/16 In. Spread — Fig. 7 1/8 In. Spread — Fig. 8 3/16 In. Spread

b—Replace with new standard size bearings.

10—*Axle Cap and Frame Bore*[8]—When the axle caps and frame are worn so that they will not clamp the bearings tightly,—

a—Weld up frame and axle cap and rebore to standard size and use standard size axle bearings.

b—Machine about 1/16 inch off at the split of the axle caps.

In addition to the ten wearing points as outlined, there are other factors to be considered which will affect the gear center distance,

TABLE I—LIMITS OF GEAR WEAR

| Dia. pitch, inches | 4¼ | 4 | 3½ | 3 | 2½ | 2 |
|---|---|---|---|---|---|---|
| Allowable spread, inches | 1/16 | 1/16 | 3/32 | 3/32 | 1/8 | 1/8 |

2—*Sprung armature shafts* should be straightened or replaced by new shafts.

3—*Armature bearings bored off center* should be rebabbitted and rebored concentric, or new correctly bored bearings used.

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[1] *For details see Railway Operating Data in June, 1924 issue of the* JOURNAL.

[2] *For details see Railway Operating Data in January, 1920 issue of the* JOURNAL.

[3] *For details see Railway Operating Data in the February, 1923 issue of the* JOURNAL.

[4] *For details see Railway Operating Data October, 1916, December, 1920, August, 1921, April, 1922, issues of the* JOURNAL.

[5] *For details see Railway Operating Data December, 1922 October, 1923 issues of the* JOURNAL.

[6] *For details see Railway Operating Data May, 1925 issue of the* JOURNAL.

[7] *For details see Railway Operating Data October, 1916, December, 1920, August, 1921 and November, 1922 issues of the* JOURNAL.

[8] *For details, see Railway Operating Data June, 1924 issue of the* JOURNAL.

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1—*Bent car axles* should be straightened.

4—*Axle bearings bored off center* should be rebabbitted and rebored concentric, or new correctly bored bearings used.

5—*Sprung motor frames* should be welded up and rebored to standard, or replaced by new frames.

6—*Bearing seat in housing bored off center* should be welded up and rebored to standard, or replaced by new housings.

7—*Loose axle cap bolts* should be kept tight by careful and frequent inspection. Only high grade heat treated axle cap bolts should be used.

While it is impossible to keep the gearing on correct center, there is a dangerous, and uneconomic point which should not be exceeded. Years of observation and study on the part of one gear manufacturer, has lead him to prepare a set of limits which should be used to guide railway operators, determining the limits of wear for their gear center distances. These limits are given in Table I.

# The JOURNAL QUESTION BOX

Our subscribers are invited to use this department as a means of securing authentic information on electrical and mechanical subjects. Questions concerning general engineering theory or practice and questions regarding apparatus or materials desired for particular needs will be answered. Specific data regarding design or redesign of individual pieces of apparatus cannot be supplied through this department.

To receive prompt attention a self-addressed, stamped envelop should accompany each query. All data necessary for a complete understanding of the problem should be furnished. A personal reply is mailed to each questioner as soon as the necessary information is available; however, as each question is answered by an expert and checked by at least two others, a reasonable length of time should be allowed before expecting a reply.

2830—SHORT-CIRCUIT CURRENT—Fig. (a) shows line diagram of our power plant and distribution system. I would appreciate having you give me the short-circuit current at point *X* on 440 volt bus and on 440 volt bus of station *D* with all generators running and Tirril voltage regulator on; and the factor you apply without voltage regulator. I would like these figures in detail so that I may check our own against them. This system serves a cement plant and we, of course, have a great deal of trouble with dust, especially on outdoor lines. We have a large production which is continuous and run this system without ground, but with a rigorous ground detection and elimination practice. Do you think that a system ground would be of any advantage and what type would you recommend; that is, resistance, straight, where made, etc. Occasionally we have short-circuits on our service lines which prove disastrous to apparatus. What would be your suggestion on a system of current limiting reactors, and where would you recommend putting them; in transformer leads or in the feeders? Our power-factor is usually carried at 94 percent.

W. G. M. (MICH.)

The solution of this problem requires considerable analytical work. Either the method outlined by Mr. Evans in the May 1924 JOURNAL or Mr. Woodward's article same issue may be used, or the method of percentages as outlined in the N. E. L. A. Relay Handbook. A complete solution for short values cannot be made without further data, particularly as regarded the 500 hp and 450 hp synchronous motors, the reactances of which are not given, and the reactance of conductor and bus bends of the 440 volt circuit. This latter is quite important. With values given on blue print and assuming 15 percent reactance for the various synchronous motors a figure of approximately 137 000 amperes at ¼ sec. after instant of short-circuit is obtained for the 440 volt power house bus. However, experience has shown that it is practically impossible to get such high values of current like 137 000 amperes on a 440 volt bus due to the reactive drop of conductor and bus bends. It is, of course, somwhat difficult to evaluate these reactances. General experience and tests indicate that the short-circuit current on 440 volt systems rarely exceed 50 000 to 60 000 amperes although calculations based on the usual components of a system such as outlined in this question may give twice as high a value. The effect of a Tirrill voltage regulator is ordinarily not noticeable until several seconds after a short-circuit has occurred. For time values less than one second the increase is approximately on the order of 10 to 15 percent. As regards the fault current on the 440 volt bus at station *D*, no data was given for the reactance of the two 400 kv-a three-phase transformers. On the assumption that three percent is approximately correct then the maximum short-circuit kv-a the two transformer banks will pass is $(800 \times 600)/2 = 26\,666$ kv-a. Allowing for a slight drop in high-tension voltage, say 10 percent, the approximate short circuit current would be $24\,000/\sqrt{3} \times 0.44) = 31\,500$. This value will be further reduced due to reactance of 440 volt conductor bends, etc. As regards operating the system with neutral grounded, changes in connections between the several substations and the two feeder lines would be necessary. Each substation should have a local 4000 volt bus with an automatic circuit breaker connection to each of the two lines. Proper directional overcurrent relays would be required at each substation. With a neutral ground a flashover on one phase becomes a short circuit and the line in trouble must be immediately taken out of service. Hence the necessity for the rearrangement of switching and relay protection. It would seem that the present system of ground detection could be continued advantageously. Regarding the use of current-limiting reactors to reduce short circuit currents, they would be most effective in the two 4000 volt outgoing feeders as doubtless most faults occurs on the outdoor lines. A five percent, 400 ampere reactor would reduce the short-circuit current on the 4000 volt lines approximately 20 percent or from 100 000 kv-a down to about 80 000 kv-a.

H. A. T.

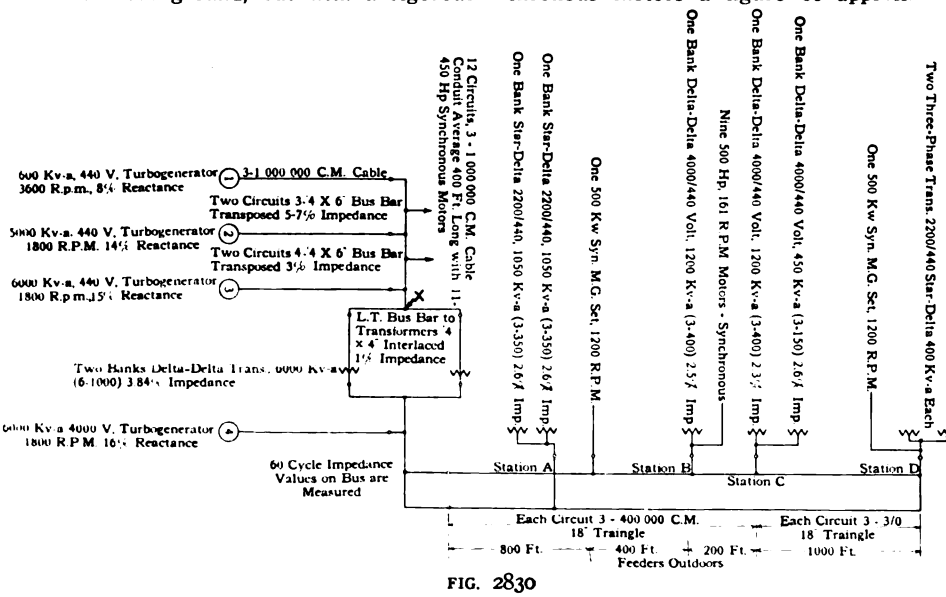
600 Kv-a, 440 V. Turbogenerator
3600 R.p.m., 8% Reactance
3-1 000 000 C.M. Cable
Two Circuits 3-4 X 6" Bus Bar
Transposed 5-7½ Impedance
5000 Kv-a, 440 V. Turbogenerator
1800 R.P.M. 14% Reactance
Two Circuits 4-4 X 6" Bus Bar
Transposed 3½ Impedance
6000 Kv-a, 440 V. Turbogenerator
1800 R.p.m. 15% Reactance
L.T. Bus Bar to
Transformers 4
x 4" Interlaced
1½ Impedance
Two Banks Delta-Delta Trans. 6000 Kv-a
(6-1000) 3.84% Impedance
6000 Kv-a 4000 V. Turbogenerator
1800 R.P.M. 16% Reactance
60 Cycle Impedance
Values on Bus are
Measured
12 Circuits 3-1 000 000 C.M. Cable
Conduit Average 400 Ft. Long with 11-
450 Hp Synchronous Motors
One Bank Star-Delta 2200/440, 1050 Kv-a (3-350) 2.6% Imp
One Bank Star-Delta 2200/440, 1050 Kv-a (3-350) 2.6% Imp
One 500 Kw Syn. M.G. Set, 1200 R.P.M.
One Bank Delta-Delta 4000/440 Volt, 1200 Kv-a (3-400) 2.5% Imp
Nine 500 Hp, 161 R.P.M. Motors - Synchronous
One Bank Delta-Delta 4000/440 Volt, 1200 Kv-a (3-400) 2.3% Imp
One Bank Delta-Delta 4000/440 Volt, 450 Kv-a (3-150) 2.6% Imp
One 500 Kw Syn. M.G. Set, 1200 R.P.M.
Two Three-Phase Trans. 2200/440 Star-Delta 400 Kv-a Each
Station A
Station B
Station C
Station D
Each Circuit 3 - 400 000 C.M.
18" Traingle
Each Circuit 3 - 3/0
18" Traingle
800 Ft.
400 Ft.
200 Ft.
1000 Ft.
Feeders Outdoors

FIG. 2830

2831—METER CONSTANTS—Kindly show how to determine the following:—register ratio, test constant, gear ratio, register constant for a 110 volt, 5 ampere, polyphase meter having a watt-hour constant of 06 used with 400:5 current transformers and 66 000:110 potential transformers.

L. C. H. (NEW YORK)

The overall ratio of the instrument

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transformers is 400/5 × 66 000/110 = 48 000/1. Test constant, the watthours per revolution of the disc = 0.6 × 48 000 = 28 800 watthours = 28.8 kw. The register constant of the meter is probably 10 000, that is, the dial reading must be multiplied by 10 000 in order to obtain the correct number of kilowatthours. It is essential that the register mechanism be such that it will not repeat within a reasonable length of time under normal operating conditions. Thus one revolution of the first pointer will equal 100 000 kw-hrs. One revolution of the disc requires 28.8 kw-hrs. Then the revolutions of the disc required to make one revolution of the first pointer are 100 000/28.8 = 3473.2. This is called the gear ratio. The register ratio is defined as the number of revolutions of the wheel meshing with the worm on the disc shaft, for one revolution of the first pointer. The reduction between the disc shaft and the first wheel is probably 100/1. Then the number of revolutions made by the first wheel for one revolution of the first pointer will be 3472.2/100 = 34.72+. C. O.

2832—BEARING PRESSURE AND BEARING LOSS—It is claimed that by reducing the pressure on bearings, or rather the bearing on the pulley side of an electric motor, the friction losses are decreased and the efficiency increased. The size of motor involved may run from 10 to 200 horse-power at any speed recommended by electrical manufacturers for two-bearing belted dry. As a specific example, assume a motor with a certain pulley size which when loaded to capacity has a bearing pressure, on the pulley bearing, of 88 lbs. per square inch, and assume further that this pressure is reduced to 44 lbs. per sq. in. Will the friction losses be decreased in like proportion or will they remain the same?

E. J. K. (ILL.)

Assuming that the journal diameter, radiating surface and load remain unaltered, the loss will be approximately in direct proportion to the area of bearing surface in action, up to the breaking point of the oil film. With the limitations given above to reduce the pressure, you must increase the length of the bearing, which also increases the area of the surface in action. This will increase the loss. Refer to THE ELECTRIC JOURNAL of September 1922 p. 376 for further information on this relation between pressure, coefficient of friction, and velocity for a perfect film. This article describes and illustrates with curves the peculiar property of a perfect film that the pressure multiplied by the coefficient of friction is approximately constant over the usual range of speeds. Hence if the pressure is reduced the coefficient of friction increases, making the losses per square inch about the same for the same speed. The result is that the loss in a given bearing is approximately proportional to the speed and is almost independent of the loading, up to the point where an oil film is no longer maintained. F. T. H.

2833—POWER-FACTOR METER TESTING—In testing a three-phase power-factor meter for correct connections and accuracy, I intend to use a phase shifting device (such as is used for making power-factor check on single-phase meters) to shift the voltage from zero to ninety degrees lead. 1—What should the power-factor meter read with phase shifter set at 100 percent; 86.6 percent; 50 percent; zero? 2—What would be the vector relations between the currents in the current coils of the meter and their resultant flux and the potential flux at these various positions of the phase shifter? S. C. M. (NEW YORK)

The correct diagram for power-factor meter is shown in Fig. (b), the voltage terminals being *A-B* and current *A-B-C* in order left to right on rear of meter. The connections shown are correct and agree with Fig. (b) except the lettered phases are advanced one letter on your diagram. The power-factor meter must have a balanced three-phase load instead of the V-connected one shown and then it will agree with the phase shifter at the values marked. The three current coils in the meter are interlaced and their resultant flux is a rotating field and cannot well be represented on a conventional diagram. The phase relations of current and voltage are shown in Fig. (c). The lettering agrees with your connection diagram and sequence *A-B-C*. The meter will read in leading quadrant. Transpose meter and phase shifter voltage leads *C* and *B* to obtain lagging quadrant. B. E. L.

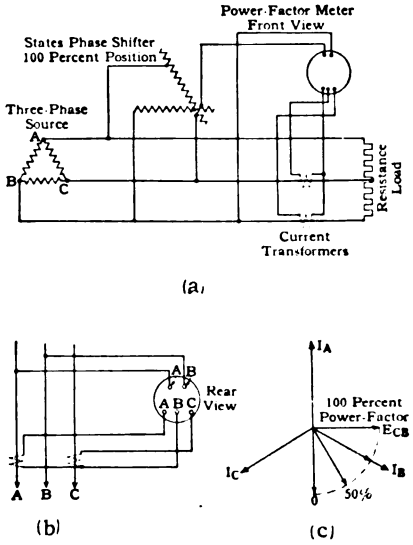


FIG. 2833 (a), (b) and (c)

2834—GROUND DETECTORS—We have an alternating-current ground detector connected to a 2300 volt bus on the primary side which is connected to three banks of transformers, stepping the voltage up to 55 000 volts on the secondary side to a high tension bus. There are four feeders from the high tension bus. When a ground occurs on any one of these feeders it shows up on the ground detector. Will you explain the theory of this. We understand that it should not show a ground on any thing but the low tension bus. A. F. J. (WASH.)

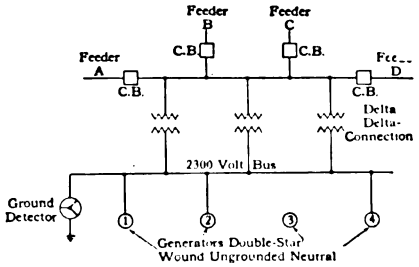


FIG. 2834 (a)

There is a certain amount of capacity coupling in the transformers so that when the feeder side is grounded, the ungrounded neutral on the generator side will shift. The electrostatic ground detector is connected as shown in Fig. (b). As long as the voltages between the indicating vane and the three stationary vanes are equal, shown vectorily in Fig (c) as *oa*, *ob*, and *oc*, the indicating vane will be held by electrostatic attraction to zero. When one of the phases on the feeder side becomes grounded, however, the neutral shifts to *o'* (Fig. d) and the voltages between indicating and stationary vanes are *o'a*, *o'b*, and *o'c*, and the indicating vane will move to a point of electrostatic balance which indicates ground. The detector will indicate correctly the phase grounded as the neutrals of both the generator and feeder side will shift in the same direction. If the capacitance of the generating system is large in comparison to the capacitance of the transformer bank, the shift in neutral on the generator side will be small and the indication on the detector will be small. If the capacitance of the transformer bank is large in comparison to the capacitance of the generating system, the shift in neutral will be large and the detector will indicate a direct ground. U. L. S.

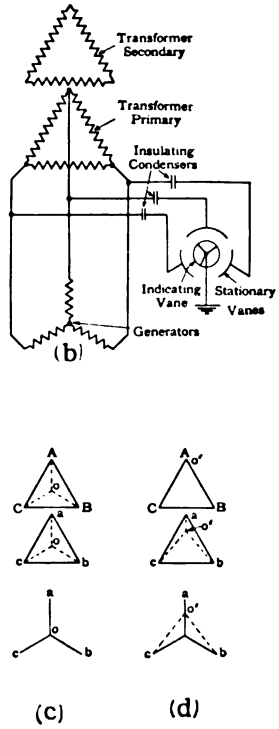


FIG. 2834 (b), (c) and (d)

2835—BUS BAR STRESSES—There are several different formulas for figuring the mechanical stresses between bus-bars. The one taken from the *Transactitons A. I. E. E.*, 1025, in an article by Schurig and Sayre is:—

$F_o = (4.5 \times 10^{-8} \times K \times I_o^2 \times l/s)$ *lbs./span*

The one taken from The Electric Journal, October 1027,—

$F = [4.5 \times 10^{-8} \times I^2 \times (l/s)]\ K =$ *lbs./span*

The one taken from the National Electrical Manufacturers Association Standards of 1927,—

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$F = (5.4\ k\ I^2\ L\ x\ 10^{-7})\ /s$ *lbs./span* Which of these formulae is best and how is the value of $4.5 \times 10^{-8}$ or $5.4 \times 10^{-7}$ determined.

H. D. C. (NEW YORK)

The first and second formulas are the same since the only difference is in the subscripts for $I$. In both formulas the bus-bar span $l$ is expressed in inches. In the formula taken from the N.E.M.A. standards the span $l$ is expressed in feet which accounts for the different form of this equation. All three formulas are correct. The force between parallel conductors is,—

$F = (2\ I^2 l\ K)/S$ where—

$I$ = current in C.G.S. units, $l$ = span in centimeter, $S$ = bus spacing in centimeters, $K$ = shape factor, $F$ = force in dynes. This fundamental formula is easily converted into either one of the formulas mentioned in the question by using the following conversion factors: 1 ampere = 1/10 C.G.S. unit; 1 pound = 444 823 dynes; 1 inch = 2.54 centimeters. The factor $4.5 \times 10^{-8}$ will be obtained if $l$ is expressed in inches and $5.4 \times 10^{-7}$ will correspond to expressed in feet. R. T.

2836—N. E. M. A. RULES ON TRANSFORMER CONNECTIONS—The N. E. M. A. Rules indicate that, when single-phase transformers are connected for star three-phase transformation, the $H_2$ or $X_2$ leads go to the star and the $H_1$ or $X_1$ leads go to the line. Fig. (a) is a sketch of two lines feeding the same bus or load. One line has two banks of subtractive polarity transformers both connected delta-delta. The other has two banks of subtractive polarity transformers, the one at the source of supply being connected delta-star and the one at the other end being connected star-delta. In this case the $H_1$ leads are to the line and the $H_2$ leads are starred. However, if the vectors as shown in Fig. (a) are correct, the two sets of banks at the load end appear to be 180 degrees out of phase. It seems to me that the connection could be corrected by starring the $H_1$ leads at the receiving end of the line. However, if this bank were replaced by a three-phase transformer, this change could not be made as the $H_2$ leads are starred in this case and could not be changed. If one delta-star bank is connected to one source of power and another delta-star bank is connected to a different source of power, which has a different phase sequence, how much will the secondaries of the two banks be out of phase? P. C. (ILL.)

In connecting single-phase transformers in three-phase banks, there is no real reason why the $H_1$ or the $H_2$ leads should go to the line, or should form the star point. In the Rules, the $H_2$ leads are shown forming the star connection merely as a matter of convention. It is not so much what leads form the star or are connected to the lines, but what is the angular relation of the primary and secondary voltages of the bank. The diagram of the vectors shown in Fig. (a) seems to be substantially correct. It is evident that the secondaries of the two groups are out of phase 180 degrees. To establish the proper conditions; on the step-down group connect the $H_1$ leads at the star point and the $H_2$ leads to the line. This will reverse the secondary voltages of each transformer of the group, and thus rotate the delta voltage of the step-down group through 180 degrees. The same result might be secured, by connecting on the step-up group the $H_1$ leads to the star connection and the $H_2$ leads to the line. The same result also could be secured by reconnecting the delta windings of the step-down transformers. If the units were three-phase and the connections all permanent, parallel operation could

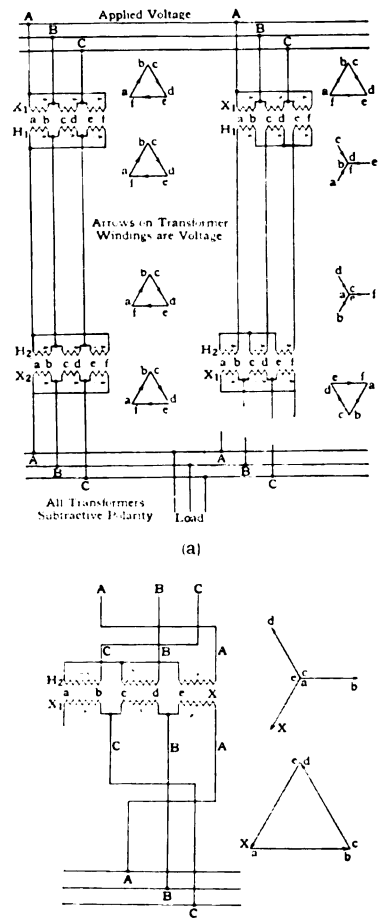


FIG. 2836—(a) and (b)

be established by connecting the step-down star-delta group as shown in Fig. (b). In two three-phase systems of different phase sequence the two systems of vectors representing the voltage will be rotating in opposite directions. Hence, the phase difference between the secondaries of your two delta-star banks will vary from zero to 180 to zero degrees once each cycle.

E. G. R.

2837—A ELIMINATOR—In question 2788 data was given on an electrolytic condenser for B-elminator use. Is there any reason why the same condenser, slightly enlarged, could not be used in a two-ampere A-eliminator? Are there other factors which would make the following reasoning unsound:—In the example given, C = 6 mfd.; E = 200 V.; therefore Q = 1200. At 12 volts, as in an *A* elminator, C would be 1200/12 = 100 mfd. per sq. in. 6 or 8 sq. in., then should be sufficient for each of the 2 or 3 blanks of condensers used, giving 600 or 800 mfd. per bank. Also, I should like a little more explanation of what is meant by the capacitance depending on the voltage of sparking. Using cells of the Edison type B-storage battery size, in test tubes ¾ in. by 6 in. as condenser cells, what would be the likely capacitance at the 12-volts of an *A* eliminator?

F. W. B. (MICH.)

The electrolytic condenser mentioned in question 2788 can be successfully used in the filter for an *A* eliminator as well as for *B* eliminator. It is not as effective, however, because the low voltage, require a great amount of capacitance to get the necessary smoothing effect. For an *A* eliminator it is found better to use batteries floating across the line in place of the electrolytic condensers, for a dry battery or a storage battery acts like a condenser of extremely high capacitance when so used. Care should be taken that the terminal voltage of the condenser be kept within limits so as to prevent either overcharging or discharging the floating filter batteries. The question indicates that you have misunderstood the data given for capacitance per square inch of anode. A condenser having the anode film formed at high voltage has less capacitance per square inch of anode than when formed at a lower voltage. Six mfds. per square inch of anode approximates the value when the condenser is formed at 200 volts. The value of 6 mfds. per square inch given in the former question, did not mean that 6 mfd. condenser is required at 200 volts, but merely meant that was the capacitance that would be obtained per unit area of aluminum plate. At 12 volts the capacitance would be greater per square inch and probably approximate 100 mfds. per square inch if properly formed. However, such high values cannot usually be realized. In the former question, the capacitance depends upon the voltage of forming up to the sparking voltage and then it decreases as a function of time of sparking. It is impossible to cover this subject completely in such an answer as this, but is well known that in any electrolyte, aluminum may be polarized up to a voltage of 100 to 500, depending upon the electrolyte, at which point, the film formed will break down by a sparking on the surface of the anode. It would be better to use the Edison *B* type storage cells as condensers across the line than to use aluminum condensers in these small tubular cells. The amount of capacitance which could be put into the tubes would depend entirely on the area of the aluminum plate which could be built into the tube. L. W. C.

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# THE ELECTRIC JOURNAL

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## Friendship in Engineering and Business

A. J. STANDING
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Superintendent Electrical Dept., Bethlehem Steel Co.

MR. C. M. SCHWAB has, on several occasions, made the statement that the greatest satisfaction in his life has come from the realization of a job well done and the enjoyment of the friendships which have come to him throughout his long and useful industrial career.

We of the Association of Iron & Steel Electrical Engineers can likewise look with satisfaction on the progress made during the past twenty years and at the same time we can count as our greatest asset the friendships which our Association enjoys among those individuals and organizations both within and without the realm of the Steel Industry. These friendships are shared by the members of the Association as well as by the body politic and to those of us who, because of our official connection, are privileged to become more familiar with the aims and objectives of the Association, these friendships mean much and involve an obligation on our part so to conduct our affairs as to continue to merit the good will and respect of our friends and associates, and to engender mutual confidence as the medium of exchange of technical information, which is one of the prime objectives of all engineering bodies.

Alfred John Standing

In the relations of our Association with other similar Engineering Societies or with the industries represented in the advertising pages of our Association publication, "The Iron & Steel Engineer", there may occur minor differences of policy or opinion which will give rise to misunderstandings and criticisms unless these points are quickly and fairly straightened out to the mutual satisfaction of all parties.

Within our Association there is the bond of friendship and common understanding among our members, scattered as they are over all the steel industrial centers of the country, that will continue to give us the prestige we now enjoy. It will be this bond of common interest and friendship that will produce leaders in our various sections, who will in turn gradually work up through the offices of the National Association.

As the years go by we will exhaust the present list of active material and it is incumbant on each Section to bring forward and develop all available talent at their command in order that our Association will always have progressive men ready to carry on the work begun by those leaders who have been the guiding power of the Association in the past.

Throughout the various major industries today we find an increasing number of positions to which one of the entrance requirements is a college degree. Undoubtedly the leaders of these industries have sound fundamental reasons back of their determination to use trained men. We are told that, as the result of a general survey of college men in certain industries, it was found that their ultimate achievements were almost directly proportional to their college scholastic records, a finding that is not entirely in keeping with the often expressed opinion that a man's progress in industry had little or no direct connection with his collegiate rating. If, as the above findings would seem to indicate, the college graduate of high scholastic attainments will unquestionably make his way in industry, we should concern ourselves primarily with the problem of stimulating the ambition and progress of the mediocre college man as he comes to our plants in the hope that by continuing to build on his college training he may in a great measure overcome the handicap of his limited scholastic brilliancy. To such men the engineering Societies are of incalculable value because they supply the field and incentive for further study and research.

The officers of the Association of Iron & Steel Electrical Engineers have for some time given serious thought to the problem of advancing the technical knowledge of those men in the maintenance departments of the steel industry who, while they may lack the advantage of college training, have demonstrated their ability and leadership in the more or less routine lines of activity. We have come to the conclusion that by means of a Junior Membership rating, entitling the holder to the advantages of the monthly publication

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of our Association in which we will strive to continually present series of articles intended for their special training, we will create a desire for similar information as contained in the kindred engineering publications of the electrical industries. We are glad to express our appreciation of the work being accomplished by THE ELECTRIC JOURNAL in its endeavor to give to its readers definite, tangible information which they can apply directly to their operating problems.

In order better to serve industry at large those of us who are in any way responsible for the work and policies of engineering societies and publications must continually strive to give to the men who constitute our membership and our reading public such material as will directly or indirectly be the means of their advancement in thought and activity.

In our Sections we should, by the continual maintenance of a friendly helpful attitude on the part of the leaders, encourage men to attend the meetings and to enter into the work of the Section by presenting papers and discussions helpful to other members, for by so doing they will also be helping themselves to acquire training which they can secure in no other way.

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# Progress and Success of Electrical Engineering

C. S. PROUDFOOT
1st Vice-President, Assoc. Iron & Steel Electrical Engineers, General Manager, Vanadium Corp. of America

CALL this age of ours anything you will; call it an age of education, or an age of democracy. But, more than any of these, this is truly an age of opportunity. Our ancestors, and our predecessors in the Iron and Steel Industry, did not dream of the glorious opportunities that exist today. In the first place, they did not enjoy our opportunities. Education, years ago, was not only costly, but exclusive. Today, the law requires a certain amount of education—but not enough. And yet, who does education benefit more than ourselves—we who, more often than not, rebelled against it?

In our own industry, for instance, it was not very many years ago that electrical engineers were practically ignored. They were considered merely as agents of a necessary evil. And what is their status today? There are many former electrical engineers holding executive positions of real importance in our own industry.

It is no secret, how many of the men at the top of the Iron and Steel Industry today got there. This is an age of opportunity—for education and self-advancement. There is no limit placed on possibilities of advancement. Whatever progress we make is entirely due to our own effort and perseverance.

There is hardly an organization in our industry that is not doing everything within its power to help their electrical men obtain a finer and more specialized education—and gladly too. Most organizations, today, provide the means, for those who are willing and conscientious, to secure the training necessary for filling more responsible positions.

Practically all electrical engineers start on an equal footing. That is, most of them have college training, and those who have, find it alone is of little avail in this very practical world of ours—where theoretical training by itself just won't do. It is the practical system of our industry that starts all on an equal footing. Previous education is an excellent foundation, but it is the education that the electrical engineer acquires after he is through with his daily work, by going to school and studying at night while the other fellow sleeps, that prepares him for bigger things.

It was found not long ago that, due to the ever-increasing amount of electrical equipment and apparatus in the Iron and Steel Industry, a general manager must be thoroughly familiar with every electrical device in the plant if he is to execute his duties properly. What could have been more logical than the discovery that the one-time ignored electrical engineer was the man most fitted and trained for the position?

Today, a salary of $3 000 or $5 000 is within the reach of any electrical engineer, and if he applies himself to specialized study, it is quite possible to earn $25 000 or more. There is one electrical engineer earning, it is said, more money than the president of the United States. This is a good example of application and perseverance. Truly, there is no limit to the possibilities of advancement for an electrical engineer.

Continually great strides are being made in the steel industry, and it is only a matter of time until the necessity of complete electrical engineering organizations will be apparent even in plants that today do not need such organizations. These organizations are already being instituted quite numerously. Naturally, they will require a number of technically trained men. And who will these men be? For the most part, they will be men who, right now, are taking advantage of their opportunities of specialized education—learning while working—opportunities which are available to everyone.

If one stops for a moment and ponders over the tremendous importance of electric power, heat and light in the Iron and Steel Industry, and the tremendous importance of our own great Industry itself, he cannot but realize the wonderful opportunities before him in electrical engineering. The field is broadening, and the need for men of broader training and understanding in engineering is increasing.

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# The Value of Electrification to the Steel Mill Industry

BRENT WILEY
Industrial Sales Dept.,
Westinghouse Electric & Mfg. Co.

AMONG the main problems of the steel industry are obtaining—first, the best quality of product within the range of materials selected; second, a uniformity of product; third, the highest rate of production without sacrifice of quality or undue rejections; fourth, minimum supervision. The use of electricity as a source of light, heat and power has been a means of solving these problems to such a degree that it is recognized today that the electrified plants are the most successful ones.

The extent to which electrification has assisted in the development of the steel industry is a remarkable story and can be only briefly sketched here. It can be shown, however, that with the progress which has been made in the various departments of the steel plant, there remain comparatively few unsolved problems in regard to reaching an ideal condition of operation with maximum efficiency.

Let us see what the use of electricity has done for the steel industry.

About forty years ago lighting was introduced in the steel industry as the first application of electricity. Today, proper lighting of the plant, particularly the finishing departments for inspection, and in the yards, is an important factor in speeding up work and eliminating accidents. The improved design of lamps and fixtures insures a desirable amount of light with limited attention to cleaning and renewals. With the introduction of flood lighting in the yards, a decided improvement in lighting is obtained even under the worst atmospheric conditions. Lighting signal systems are used to good advantage in numerous applications in the mills as a guide to the operators.

THE next application of electricity was in connection with auxiliary drives. As one engineer has remarked, the advantages of motors for auxiliary machines in a steel plant are too numerous to mention. Perhaps one of the best ways to emphasize this point is to consider what it would mean to eliminate the use of motors.

Aside from electricity, the two common classes of power that remain in the plant are steam and hydraulic. If these power sources only were available, think of the limitations to the design, speed and variety of auxiliary machines now so successfully operated by motor drive, including overhead cranes, charging machines, other types of conveying machines, tables, screwdowns and all classes of finishing machinery.

The layout of the mill is much more flexible with motor-operated machines, as they are a complete unit in themselves, and the wiring is convenient and cheap to install as compared with the piping necessary with either steam or hydraulic power, especially for remote locations.

The maintaining of a motor-operated auxiliary system is a much smaller item than for systems where steam and hydraulic units only are used, as the latter require frequent inspection and numerous repairs. As a whole, it is doubtful if any steel plant organization would be able to put themselves in a competitive position if they were denied the use of motor drive for the many auxiliary machine applications.

THE next step of development included the application of large motors to the main roll drive. Undoubtedly this improvement includes the greatest advantages which electricity affords the steel industry. It has been the main factor in speeding up the mills, improving the product and eliminating labor and general supervision. The steel officials have made the statement that by completely electrifying their mills, reduction in production costs of four to eight dollars per ton have been effected; and the major portion of this saving is in the rolling of steel.

During the last twenty-three years all classes of mills have been electrified, from the small merchant mill to the heavy, reversing blooming mill. The record of production of these various classes of mills has continued to improve, and the improved characteristics of motor drive have played an important part in bringing mill production to the present high rate.

A decided feature of economy in steel-mill electrification is the generation and distribution of power. Waste gas and waste heat are utilized to generate steam from which the turbine-driven generators are operated. In a few cases the waste gas of the blast furnace is used directly in gas engines. The concentration of power generation into a single plant or single system is a great advantage, giving a more uniform load condition and insuring the proper characteristics of power at the point of utilization. In the case of the steam-driven mill every mill man knows the problems and draw-backs incident to low steam pressure and limited supply. The proper voltage and ample supply of power is the slogan of every electric power station, and it is seldom that this slogan is not lived up to.

Where the location makes it feasible, the large steel companies are consolidating the power plants of their various properties into a single unit, similar to the practice of the large central stations. The Car-

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negie Steel Company is at the present time tying together several of their large properties located along the Monongahela River. In other cases a tie-in with central stations is being effected by steel plant power stations and in these cases power is furnished to the central station at off-work periods and the central station supplies any deficiency should there be an over demand on the steel plant power house.

There are several general applications throughout the steel plants which are also becoming important factors in regard to the general efficiency of operation. Industrial heating devices, including tempering and annealing furnaces of the electric type, are capable of accurate control, and in a sense can be classed as automatic. The exact conditions for the proper treatment of the steel, as prescribed by tests, can be duplicated and maintained, thus insuring a definite and uniform quality.

Electrical devices for inspection of the finished steel are a possibility, making this important phase of the work more accurate and dependable, with a material saving in time.

Electrical welding is a growing factor in the economy of repairs in the steel plant. A welding bureau in a large steel plant can easily be made to pay a large return on the investment. Electrical welding is also playing an important part in steel construction work. Each year there is an increase in the number of welded buildings and bridges built.

Electrically-operated locomotives are assisting in solving the transportation problems in the steel plants, particularly in reference to yard service. During the last two years the oil-engine electric locomotive has been selected in several cases for switching and general yard work and the demonstrations made are very favorable as compared to the use of the steam engine.

To visualize a steel plant automatically controlled or pushbutton-operated from the blooming mill to the shipping department might seem to need the imagination of a Jules Verne, but such a manufacturing system is, in the main, a possibility, not only in connection with the auxiliary but also with the main roll drives.

The control of auxiliary machines has done a great deal toward eliminating personal supervision of individual operations. The tendency of improvements is toward automatic operation and interlocking control systems, so that the proper sequence of starting, adjusting and stopping of the machines in the system is secured. For instance, the covers of the soaking pits of a blooming mill are now controlled by the pit-crane operator, who also runs the ingot buggy. Thus, one operator delivers the ingot from the soaking pit to the mill table. There are numerous examples such as automatic shearing, automatic transferring of the metal, etc., where the work is performed practically independent of the operator.

In regard to main roll drives, a structural mill installed two years ago in the Pittsburgh district is a good example of the progress which has been made toward automatically-operated plants. In this mill there are three sets of rolls working on the steel at the same time—two main horizontal sets of rolls and a set of vertical rolls. One set of horizontal rolls and vertical rolls are driven by a large reversing motor and the other set of horizontal rolls is driven by a second reversing unit. It is essential that proper speed relations be maintained at all times between the three sets of rolls. The ratio of the speed of the two motors varies with the direction in which the metal is rolled and with the draft, and correct ratio must be maintained when the speed of the motor in either direction is increased, decreased or is constant. Naturally the three screw-downs on the mill must be automatically controlled and so interlocked that proper adjustment is secured for each setting.

The entire mill consists of a roughing mill, intermediate mill and finishing stand with a total of seven sets of rolls and as many screw-downs, with the usual mill table and other required auxiliaries. The force required to operate this mill consists of one man in the roughing mill pulpit, one man in the intermediate mill pulpit and the third man who operates a drag-over transfer between the two mills. Thus, only three men are required to control every operation of the steel from the time it leaves the blooming mill in the form of a rough blank until it is a finished product.

Although the mill just mentioned is not completely automatic, it approaches closely this ideal arrangement and is certainly quite in contrast with mills of older types.

Another type of mill which illustrates this idea of reduced supervision is the continuous mill for producing rods, bars and wide strip steel. A few years ago the design of a tandem-type mill was largely limited to a lay shaft proposition, as it was not considered feasible to drive several stands by individual motors on account of the problem of speed regulation.

The flexibility of the modern tandem mill is a wonderful improvement over the old design. It provides a ready method of obtaining the proper adjustment of the mill as required for a wide range of product, and as required to obtain uniform and accurately finished material. Individual motor drive has made the development of the modern design of tandem mill possible.

During the last year a number of unusual individual motor-driven equipments have been ordered and several of the mills are in operation at present. The American Sheet & Tin Plate Company have installed a tandem-type hot strip mill at their Gary, Indiana, plant which uses six 2500 hp, 160/320 r.p.m., 600 volt, direct-current adjustable speed motors. This mill was put in operation in the fall of 1927. The American Rolling Mill Co., are installing this year at their Mid-

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dletown, Ohio, works the heaviest motorized strip mill in the country. The drive for the finishing portion of the mill will consist of four 3000 hp, 180/360 r.p.m., 600 volt adjustable speed direct-current motors.

The above large motor units have wonderfully close regulation over the full speed range from no load to full load. A mill of this type is continuous in operation from the time the piece enters the first stand until it is a finished product; and it requires very little supervision by the operators after it is once adjusted.

It is evident from the rapid progress of development along the lines mentioned above that we will soon have the completely electrified mill; to a large extent it will be operated automatically, and the supervision required will be, with a few exceptions, of a general nature. All of these improvements tend toward a better quality of product and greater efficiency of operation

# The Electrification of No. 3 Rod Mill

## At the Worcester Works of American Steel & Wire Company

G. P. WILSON
Steel Mill Engineer,
Westinghouse Electric & Mfg. Co.

THE year 1927 saw the addition to the steel industry of another high-speed continuous rod mill. This mill is installed in the South Works of the American Steel & Wire Company, at Worcester, Mass. It is driven by three direct-current motors, one of which is 3000 hp, 50° C., 600 volt, 180/370 r.p.m. The other two are each 800 hp, 50° C., 600 volt, 535/750 r.p.m. These motors receive their power from three 1500 kw nominal rated, 600 volt, 600 r.p.m. direct-current generators, each driven by three-phase, 60 cycle, 13 200 volt, 12 pole, 80 percent leading power-factor synchronous motors. Only two of the motor-generator sets are needed for carrying the mill load. The third set is used as a spare. It probably will be required, however, for continuous service in the near future, inasmuch as rod mill No. 2, which is now being installed, will receive its power from this substation.

In addition to these three sets there are also installed two 1000 kw, 250 volt direct-current synchronous motor-generator sets. The motors of these sets are also 80 percent leading power-factor, three-phase, 60 cycle, 13 200 volt. These sets are used for furnishing power to the auxiliary motors on the mill and conveyors. A total of 9000 hp of motors is installed for the main drives and auxiliary equipment, all receiving their power from the motor-generator sets. An additional 2500 hp in alternating-current motors are connected to the transformers.

This mill replaces two old mills and the above motors replace eight steam engines. Quite a record was made by the operating staff in installing the new mill and its electrical equipment. The old plant was closed down the night of July 1st, and the first rod (No. 5) was rolled in the mill on August 17th. Especially is the operating force to be commended when it is considered that the new mill was installed on the site of the old mill. This condition added many difficulties. It included not only the installation of miles of new sewers, water mains, electrical cables, and conduits, motor foundations, buildings, cranes, motor rooms and substation, but also the removal of many tons of old machinery and foundations, and the excavation for the installation of the new mill and motor foundations. It is true that a great deal of this work was done while the old mills were still operating, which in itself was a considerable achievement and added many difficulties to be overcome by those in charge of the work.

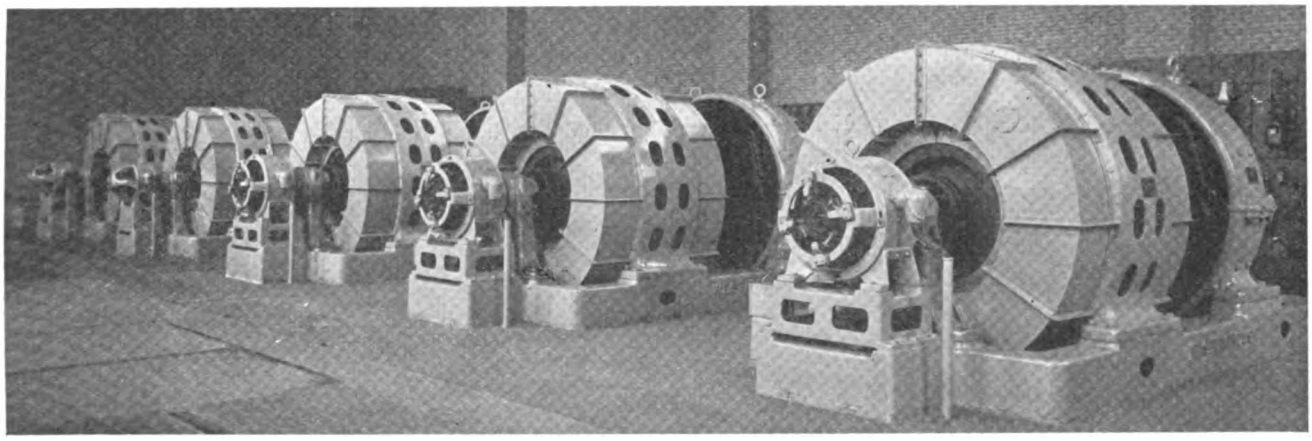

FIG. 1—NEW MOTOR-GENERATOR SUBSTATION OF THE AMERICAN STEEL AND WIRE COMPANY AT WORCESTER, MASS.

Central station power is used for operating this mill, as well as the rest of the plant. The New

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England Power Company furnishes the current from its Millbury substation. This substation is amply provided against power failure by ten high-tension lines which interconnect at different points of the system and come to the substation over six separate rights-of-way. The power from this substation is carried on three separate pole lines over two rights-of-way approximately four miles to the edge of the plant's property. From here it is carried in underground cables to the mill substation. The transformer substation is located just outside the mill motor room, and contains two banks of three 1000 kv-a, single-phase, 13200/2200 volt transformers which supply auxiliary power for the South Works. The power for the motor-generator sets is taken from this substation at 13 200 volts through underground cables, which terminate on busses located in the basement of the substation. Separate busses are provided for the 250 volt group and the 600 volt group of motor-generator sets. In addition to

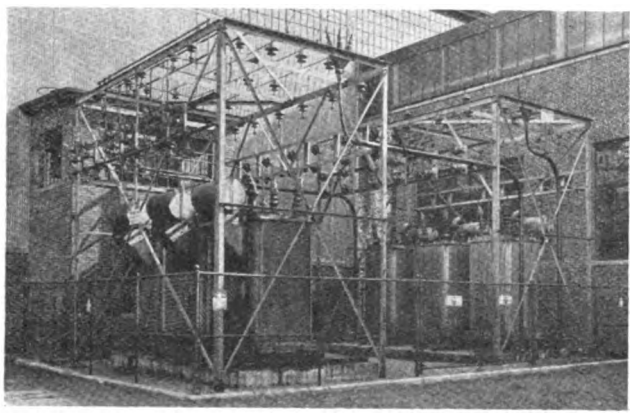

FIG. 2—OUTDOOR TRANSFORMER SUBSTATION
This substation includes six 1000 kv-a, oil-insulated, self-cooled, 13 200/2300 volt, single-phase transformers.

the above equipment there are also located in the basement the 2300 volt bus, a 450 kv-a, 440 volt, three-phase, auxiliary transformer and a 200 kv-a, 110 volt, single-phase lighting transformer, all the oil circuit breakers, and the control for the direct-current motors and the motor-generators sets.

The sets have reactance coils in place of standard autotransformers for furnishing reduced voltage to the terminals of the machines under starting conditions. The substation operator starts and stops the 600 volt sets. The two 250 volt sets are started by means of pushbuttons located on the main alternating-current control panels for these sets. These sets are equipped with standard underload and overload relays, which either shut down or start up the second unit, depending on the load demand, and voltage reducing relays which protect the machine against sustained overload by reducing this voltage and maintaining full-load current. The 600 volt sets are not equipped with these load-response relays, but are under the direct control of the substation operator.

The direct-current feeders on the 250 volt equipment are provided with automatic reclosing circuit breakers and relays. There are ten feeders, all of 2000 amperes capacity.

The mill substation which houses the motor-generator sets, control, and switching equipment is of brick construction approximately 100 ft. long by 60 ft. wide.

FIG. 3—THE MAGNETIC CONTROL FOR THE ROD MILL MOTORS

A basement extends the entire length of the substation. The control panels for the motors are located in the basement, as well as the oil circuit breakers mentioned above. These control panels are of the magnetic type, with current accelerating relays. The panels on which are mounted the circuit breakers, contactors and relays, are ebony asbestos board, two inches thick with one-fourth inch bevel. They are mounted on angle iron frame-work supported on a six inch channel cemented in the floor. Fig. 3 shows these control panels installed as a continuous board, with the starting resistors for the motors mounted above and back of the panel. Ample room is provided both in the front and rear of the board for inspection and maintenance of this equipment.

Also located in the basement are the exciter sets which furnish excitation to the motors and motor-gen-

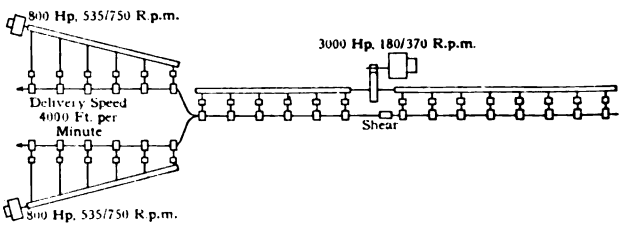


FIG. 4—SCHEMATIC ARRANGEMENT OF THE ROD MILL AND DRIVING MOTORS

erator sets, the rheostats for the motors and motor-generator sets, and the starting reactors for the sets. The motors are located outside the substation in individual motor rooms. Fig. 4 shows a schematic layout of the mill and the approximate location of the

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motor rooms with respect to the mill and the main substation. The design of one of these motor rooms is shown in Fig. 5. Fig. 6 shows one of the 800 hp motors located in this motor room. This picture is taken from the commutator end of the motor and shows the overspeed device and the speed indicating magneto. These attachments are driven by means of gears fastened to the end of the motor shaft. All motors are provided with light thrust collars of special design to take momentary thrust. The location and general construction of these thrust collars may be seen on the 3000 hp motor in Fig. 7.

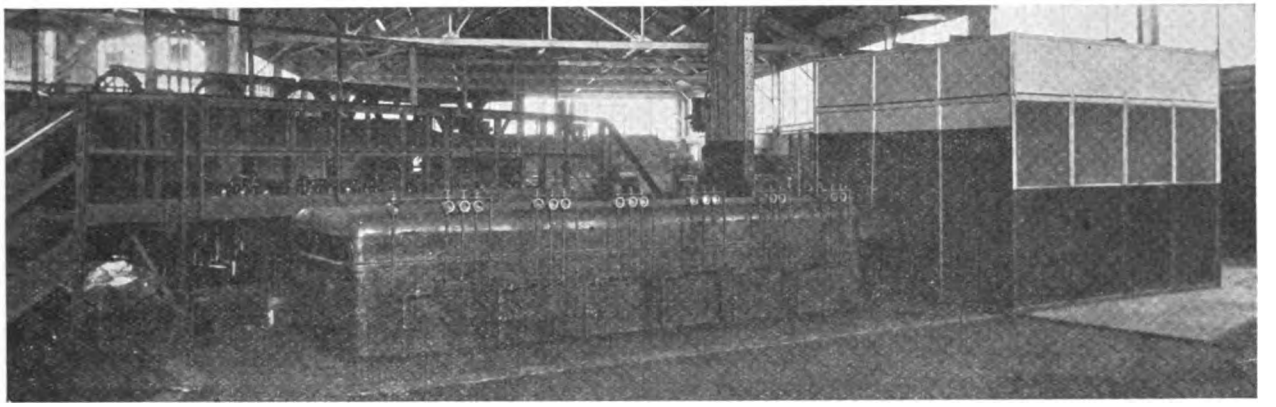

FIG. 5—ONE OF THE FINISHING TRAIN OF STANDS
Showing the method of housing the 800 hp motor driving one of the finishing mills.

The operator's pulpit, as indicated in Fig. 8, is located at the side and above the finishing end of the mill directly opposite the space between the roughing and the finishing train. This pulpit, as indicated in Fig. 9, is glass enclosed and contains the control desk for the motors. This desk is of all steel construction, approximately 6 ft. long by 2.5 ft. wide by 2.5 ft. high. The top of the desk is inclined approximately 30 degrees and has mounted on it a voltmeter to show that the main 600 volt power is ready, pushbuttons for starting the motor, ammeters calibrated in horse-power for the three direct-current motors driving the mill, speed indicators, a pushbutton for the control of the rough speed adjustment of the motors, and vernier rheostat operating handles for close speed adjustment of the motors. These rheostats are chain operated and are located underneath the floor of the pulpit. Field reversing switches are mounted on the front of the desk. These are knife switches of the back-of-board type. The handles extend through the front of the desk and are easily accessible to the operator, in case he should desire to reverse the direction of rotation of the mill motors.

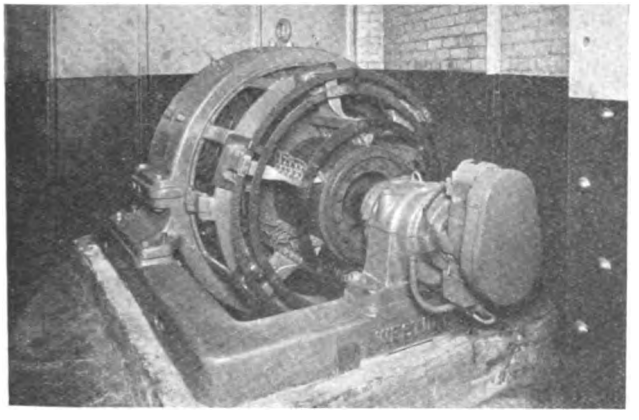

FIG. 6—AN 800 HP, 600 VOLT, FINISHING MILL MOTOR
Showing the overspeed device and the speed indicating magneto.

The motors are especially designed for the inherent close speed regulation which is required for this type of mill. To obtain the desired regulation, it was necessary to provide the motors with an adjustable series field winding, as well as compensating or pole-face windings, in addition to the standard shunt and commutating-field windings. Very desirable speed characteristics were accomplished in the design of these machines, as shown in Fig. 12. It will be noted from the curves that the motor has practically flat speed regulation from no-load to twice full-load, at different speeds from full field speed to maximum weakened field speed. This is remarkably close speed regulation when it is considered that the motor has a speed range of 2 to 1. It was essential, however, that this good speed regulation be obtained, or otherwise the operation of the mill would have been handicapped.

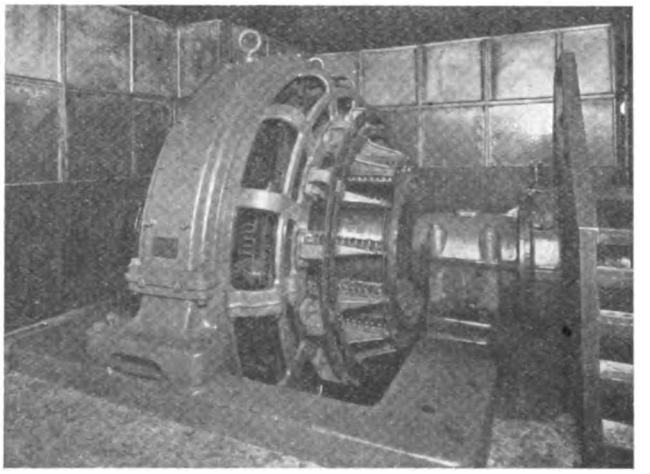

FIG. 7—A 3000 HP, 600 VOLT, ROUGHING MILL MOTOR
Illustrating the interior of one of the motor houses.

The auxiliary motors on the furnace, muffle con-

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veyor, fans, hook carrier, feed rolls, mill tables, etc., are of the enclosed mill type. These motors are provided with special compound field windings to limit the speed increase to 50 percent. The control for these motors is of the magnetic type, as shown in Fig. 11.

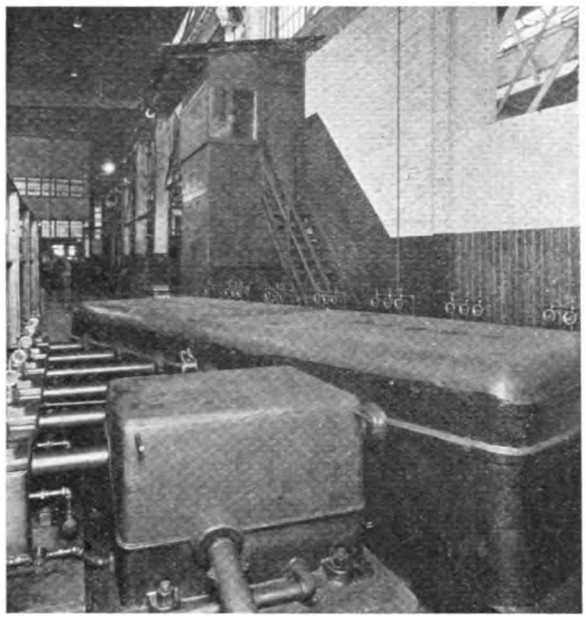

FIG. 8—THE PULPIT CONTROL DESK
Where the operator has full view of the entire mill and controls the operation of the 3000 hp and the two 800 hp adjustable speed direct-current motors.

The entrance service switch for the board is of the safety type and may be seen mounted at the end of the board in Fig. 11. The complete control board has all the apparatus mounted so as to give a neat and symmetrical appearance.

FIG. 9—THE PULPIT CONTROL DESK

The mill has been in continuous operation for nearly a year and the motors, as well as the rest of the electrical equipment, have performed very satisfactorily. There have, of course, been some delays, but they all have been of minor importance. The mill is now operating at approximately full capacity, turning out steel at the rate of 100 000 tons a year. The power costs on the mill may be judged from the power consumption, as given by the operating department for the month of April, 1928, when rolling No. 5 rod from 2 by 2 inch by 30 ft. long billets. During April the mill averaged 106.2 kw-hours per ton for the main

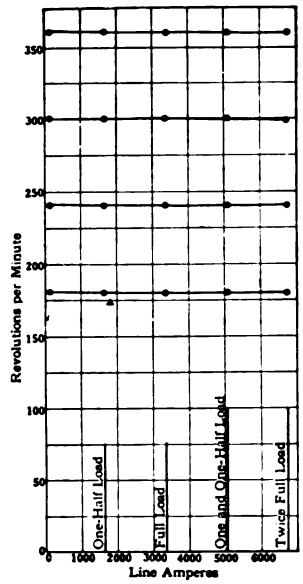


FIG. 10—SPEED REGULATION CURVES OF THE 3000 HP, DIRECT-CURRENT MOTOR
As taken in the factory when the motor was on test.

drives. The auxiliaries averaged 1.6 kw-hours per ton. Included in the auxiliaries are the various drives around the furnace, muffle conveyor and hook carrier. Considering that the mill has been operating less than

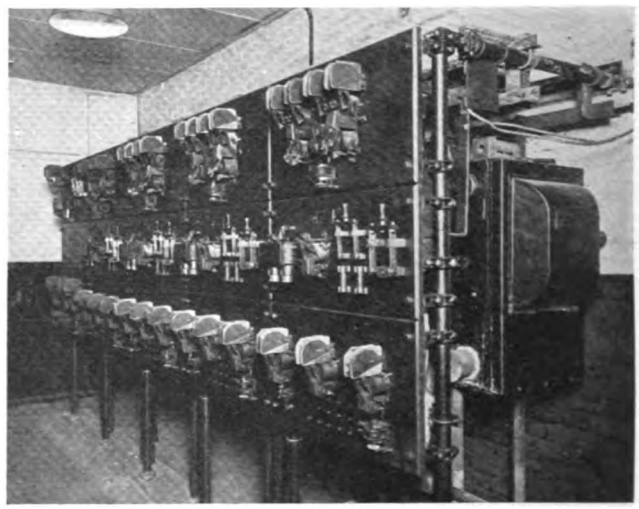

FIG. 11—THE MAGNETIC CONTROL FOR THE FIVE AUXILIARY MOTORS
Which drive the muffle conveyor and hook carrier.

a year, the above figures for power consumption are very satisfactory. It is expected, however, that these figures will be reduced as the mill increases its production.

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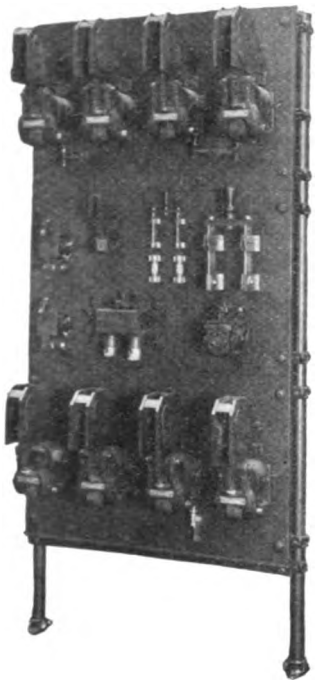
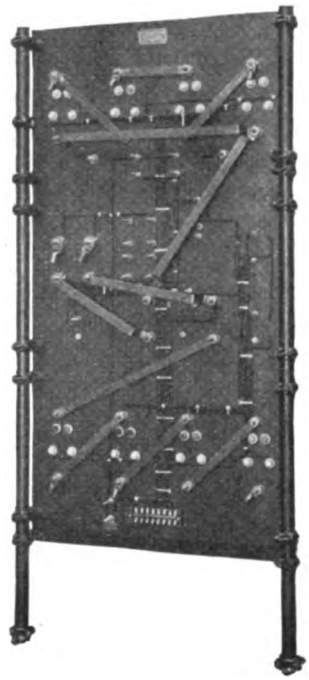
# Inductive Time Limit Control



FRONT VIEW OF CONTROL PANEL

W. G. COOK
Control Engineer,
Westinghouse Electric & Mfg. Co.

**The credit for having successfully disposed of some of the most difficult mechanical problems in industry belongs to the steel-mill designer. With only steam and hydraulic power available as prime movers, the methods employed in the manufacture of steel were comparatively crude, but with the advent of the perfected electric motor and its necessary auxiliaries, the crudeness has been transformed to precision.**



REAR VIEW OF CONTROL PANEL

MECHANICAL developments in the steel mills are each day setting more and more stringent requirements, both to the operations or sequences which the electrical equipment must perform and to its durability. Though it is not usually difficult to secure practically any electrical sequence of operations, the number of parts involved may become excessive, making both an expensive and a complicated application, with many chances of failure. Each new requirement, however, has been met with an honest attempt to fulfill the operating conditions—resulting in the development of new apparatus and the discard of old. Though this is true of all the mill electrical equipment, the purpose of this paper is to discuss in detail only the recent developments in the auxiliary motor control.

The fluctuation of line voltage, prevalent in some mills, combined with the friction load variations due to temperature changes, have shown that the counter-electro-motive-force, lockout contactor, and to some extent, the current limit systems of acceleration are unsatisfactory. When it is considered that the torque which must be exerted to start the table rolls, manipulators, screw downs, cooling tables, etc., on a cold Monday morning may be several times the normal value, it is evident why the counter e.m.f. system has failed and why, in many applications, the current limit system is falling short. For a reasonable range of load conditions the current limit system is theoretically correct, since with this method, the motor will always accelerate as rapidly as the degree of protection, previously determined by relay settings, will allow. There are, however, short intervals, such as the above, when abuse of motors, mill drive, and control seem to be warranted by the benefits to be derived, as all the stiffness disappears after the mill is in operation for a short time. Even with the current limit system, the motors are forced to operate at the present time by setting the relays for higher than normal currents. During this period, the electrical equipment is performing under severe strains, but the all important production schedule is not being delayed, and in a short time the relays may be reset for normal operation.

The annoyance and expense of continually having to make adjustments, combined with the continuous severe duty imposed on the motors, due to incorrect re-adjustments of control relays, has created a demand for a system which will place a motor on the line whether it will rotate or not, and then if it is "frozen", remove it promptly. In nearly every case, when the first or second step of resistance has been short-circuited, and several times full-load current is being circulated through the motor, it will start, and there is no further trouble.

These statements are illustrated by the curves of Fig. 1, where the time is that required to accelerate the load. If the ordinate $X$ represents the average value of starting torque, then curve $A$ might be assumed as a typical current-acceleration curve. Should there be a shut-down for any reason, and the drive becomes stiff, the line $Y$ might represent the necessary break-away motor effort. Obviously, the motor would not start unless the current limit relays were reset to allow the first accelerating switch to close with stalled motor current, as at $B$. After a short running period, the friction diminishes, and if the relays are not

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given their original settings, curve *C* might represent the accelerating current of the motor. At this time the ambient temperature has risen, the load is coming up to speed unnecessarily fast, at the expense of the motor. Had some "definite time" or other forced acceleration method of control been employed, the motor would have started under the heavy load without any adjustment of relays, and then since the time

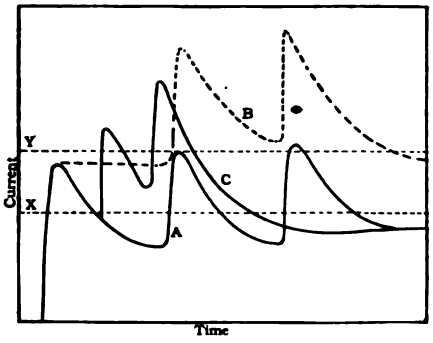



FIG. 1—TYPICAL ACCELERATION CURVES

of closure of accelerating switches does not depend on current settings, would have been subjected automatically to the normal running conditions. That is to say, while the initial conditions might be represented by curve *B*, a family of curves would be described between *B* and *A*—each one with smaller peaks, approaching the limit *A* as the mill temperature rose.

To be successful, equipment for such operation must be electrically adequate, must be easy to manufacture, and have a long life with a minimum of adjustment or attention. One of the most promising of such control schemes is that here described, which embodies all the above essential characteristics combined with simplicity, not only in theory, but also in application. Two new types of relays have been developed and since their principles of operation are unique, a short description of them is given first.

The relay shown in Figs. 2 and 3 has been designed to indicate on the control panel the direction of rotation or the direction in which the motor would rotate if sufficient torque were available. It is used only with the plugging-reversing type of control, where it is desirable to short-circuit the plugging step of resistance immediately on starting the motor from rest; and to hold it in circuit, limiting the excessive current peaks, when the motor has been plugged. Should the master switch be placed in the forward position when the motor is at rest or going forward, this relay, being polarized, will make a forward contact, and the control connections are such that the plugging step of resistance is short-circuited. If the motor is rotating in the reverse direction when the master switch is thrown

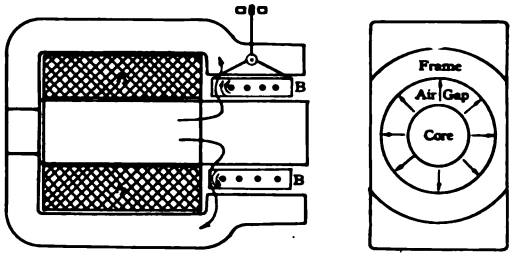
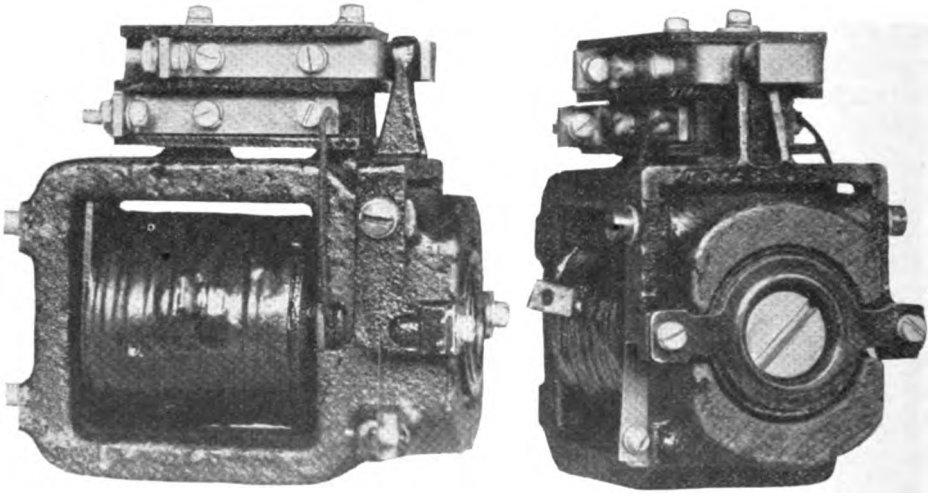



FIG. 4—MAGNETIC CIRCUIT OF PLUGGING RELAY

forward, the plugging step of resistance is held in circuit until the motor practically comes to rest, thereby assuring always the equivalent of starting a motor from standstill, though the reversing is accomplished under a percentage of full load current predetermined by the ohmic value of the starting resistor.

The relay itself is a sensitive, yet unusually rugged two coil piece of apparatus responding to a voltage as low as 10 or 15 volts, yet capable of withstanding 250 volts continuous duty. This wide operating range has been obtained by the adoption of the magnetic circuit illustrated in Fig. 4. The main coil *A* is connected to a constant source of potential, and sets up a polarizing flux in its air and iron magnetic path, as indicated by the arrows. The second coil *B*, whose movable support serves also as a contact finger, capable of making either a forward or reverse connection, works in the radial air-gap between the iron core and outside frame.

The radial gap was employed since its effective cross section is a maximum, thereby reducing the reluctance and increasing the flux for a given size of main coil. The requirements of the main or polariz-



FIGS. 2 AND 3—FRONT AND SIDE VIEWS OF TYPE PR PLUGGING RELAY

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ing coil are, briefly, to set up a certain amount of flux, and to dissipate the heat due to the $I^2R$ loss. The torque exerted on the movable or floating coil varies not only directly as the current through it, and therefore, the voltage applied to it, but also directly as the number of flux lines in the main magnetic circuit, and its direction of movement depends upon both the direction of the main flux and that due to its own excitation.

FIG. 5—MOVABLE COIL OF PLUGGING RELAY

When the excitation of the two coils is such that the flux relations are as indicated in Fig. 4, the torque exerted upon the movable coil tends to move it towards the left, and the corresponding electrical connection is made. When the excitation of the movable coil is reversed, the coil will move toward the right. The control schemes have been so designed that neither the PR or TL relays ever break a current-carrying circuit. This means that, as there will be no arcing, the necessary contact gap is a minimum, which in turn permits comparatively small coil movement. As the coil moves in the arc of a circle, the smaller this movement, the less air-gap clearance will be necessary; hence, the greater field strength and a greater torque for a given rating or size of main field coil. The wear on the bearings supporting the floating coil, the only moving part, is likewise reduced to a negligible degree. Further efforts in the development of a rugged relay have resulted in bringing the leads of the moving coil out through the frame, as shown in Fig. 3, insuring their protection from mechanical damage as well as providing a means of making electrical connections.

The idea of sturdiness was not neglected even in the construction of the movable coil, a particularly difficult proposition since a 250 volt coil had to embody compactness to the last degree, appreciable field

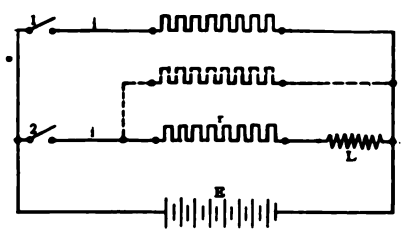


FIG. 6—NON-INDUCTIVE AND INDUCTIVE CIRCUITS

strength, contain no iron and be so rigid that it can be supported by one end washer only—yet withstand terrific shocks, such as exist in crane service. Fig. 5 shows the assembled coil, making use of a completely insulated spool with an additional winged, supporting aluminum stamping, the spool and the aluminum washer being held rigidly together by a brass inner tube whose ends have been spun to form a flange.

As mentioned, the PR relay takes care of merely the plugging step of resistance in a reversing plugging controller. The accelerating switches are energized through inductive time relays which work upon a flux decay principle.

When there is a change in the electrical potential applied to an inductive circuit, there is a corresponding gradual change in the current flowing through it. This is illustrated by Fig. 6, where $L$ = inductance, $r$ = resistance, $E$ = applied voltage, $R$ = reluctance, and $i$ = instantaneous current. Branch 1 is assumed to be non-inductive while branch 2 is assumed to have the same resistance as 1 and also be very inductive. When switch 1 is closed the current $i$ in its circuit is immediately equal to $E/r$, but when switch 2 is closed the current in circuit 2 is small at first and gradually increases until it also equals $E/r$. As circuit 1 is non-inductive, there are no lines of flux linking it, while the current in circuit 2 is linked by its own flux and

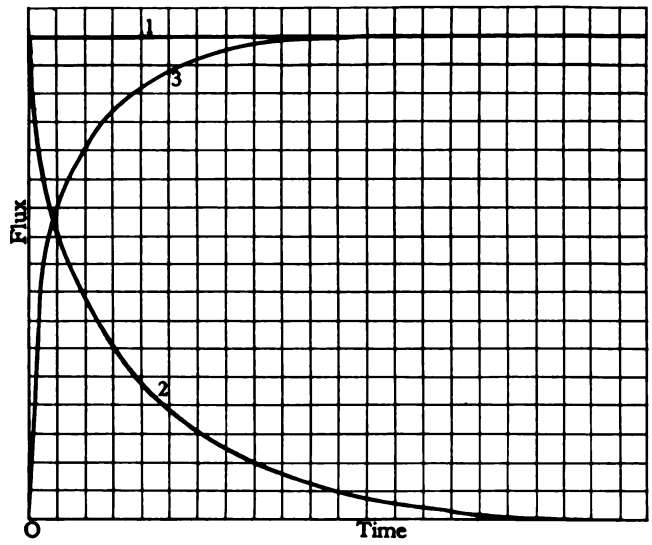


FIG. 7—CURRENT CHANGE IN NON-INDUCTIVE AND INDUCTIVE CIRCUITS

there is generated in it a counter voltage equal to $\frac{d}{dt}(Li)$, the rate of change of the flux linkages. The current at any instant after the closure of the switch is represented then by $i = \frac{E - \frac{d}{dt}(Li)}{r}$. That is to say, it is equal to the instantaneous voltage divided by the resistance. This relation is represented by curve 3 in Fig. 7. The current in circuit 1 reaches its final value immediately, while in 2 it approaches the final value only after an appreciably time, depending on the ratio of inductance to resistance. When switch 1 is opened, the current falls instantly to zero, but when switch 2 is opened, the current decreases according to the law $i = \frac{E}{r} \varepsilon^{-\frac{rx}{L}t}$ where $rx$ is the effective resistance of the entire coil, discharge and iron circuit. In the second case, the e.m.f. generated by the decay of flux tends to maintain the flow of current, as shown by

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curve 2 of Fig. 7. Curves of flux might be plotted having the same relative shapes as those of current—anything tending to increase the inductance and decrease the resistance of the circuit tends to make the flux changes more gradual and tends to require a longer time for the steady state condition.

Obviously the use of curve 3 is desirable in the design of a time limit relay dependent on a magnetic change, since its electrical circuit might be energized and then after a definite time the relay would close. If curve 2 is utilized the relay first must be picked up, then something in the control circuit must deënergize it, and finally the relay opens. It is not always easy to obtain such a sequence.

From an application standpoint, it is unquestionably desirable to use an inductive device depending on the building up (curve 3) rather than the decay of flux (curve 2), since much better contact pressures are available and since practically all electrical interlocks are readily eliminated from control circuits. There are several disadvantages, however, which practically eliminate the possibility of its use.

The ratio of $L/r$ is inherently very small, as the inductance varies inversely with the reluctance, and the reluctance of the magnetic circuit is very large when an air-gap is present. The time of closure for a given relay is therefore reduced to a very small fraction of its drop out time. A variation of line voltage not only will vary the time of operation, but, in cases of reduced voltage, will cause a failure.

Since the holding flux of any relay having a good magnetic circuit is but a small percentage of that required for pull in, a relay employing a flux decay principal may utilize comparatively minute changes for

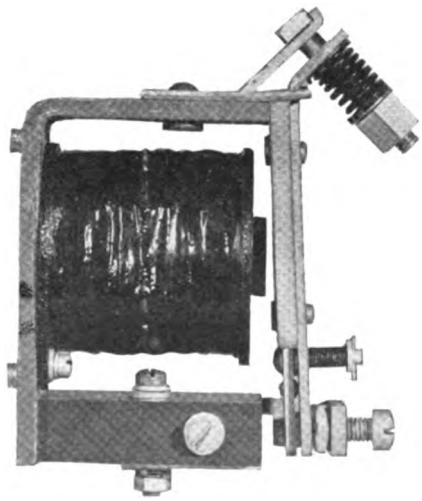

FIG. 8—SIDE VIEW OF TYPE TL INDUCTIVE TIME-LIMIT RELAY

positive and accurate operation. This is especially important since there is a small change which takes place during a relatively long period, as shown in Fig. 7.

The above ideas are incorporated in several types of relay which are giving good service when correctly applied. Even with the relays working on the flux decay principle, however, the time elements of some present types are rather short, and when longer settings are desired the kickout spring pressure is very weak, resulting in poor contact pressure. Too short a time interval between successive accelerating switches results in too rapid motor acceleration, as shown in curve B of Fig. 1, or an excessive number of relays and contactors—an expensive proposition both from an initial cost and maintenance standpoint.

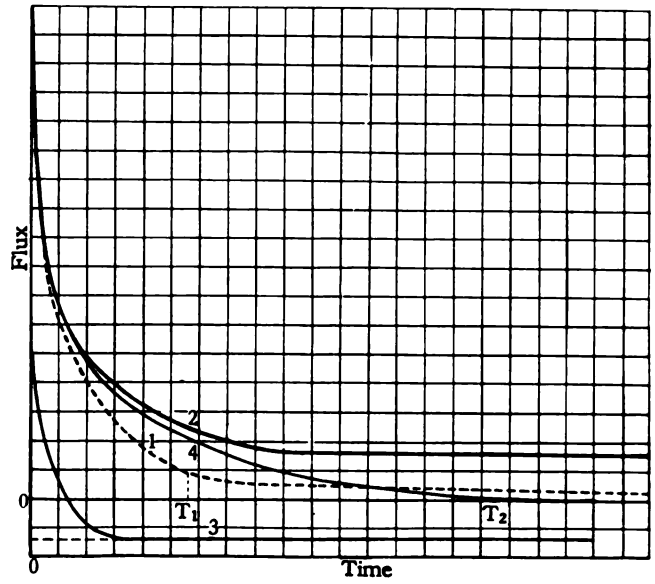


FIG. 9—FLUX DECAY CURVES IN THE TL RELAY

To meet the demand for a larger time range, stronger contact pressure and mechanical simplicity, there has been developed a new inductive time limit relay shown in Fig. 8. Two sizes are being manufactured, one, a general purpose relay, suitable for all direct-current motor acceleration, whose range is about two-tenths to two seconds, and a second relay whose range is about one to eight or ten seconds. These exceptionally long times have been obtained not by increasing the iron and copper, but by utilizing to the utmost the gradual but certain flux change described above.

Until the present developments, all contactors and relays having good magnetic circuits had to have artificial air-gaps or almost prohibitive kick out spring pressures to prevent freezing. Not only does an air-gap serve as a demagnetizing force to reduce residual but, as shown previously, the ratio of $L/r$ is decreased and more flux is required to keep the armature sealed. Through the employment of an electrical neutralizing or demagnetizing winding, the TL relay eliminates the artificial gaps, and their variations, and amplifies the desirable characteristics of the decaying flux curve to an extended degree.

The curves of Fig. 9, are typical flux-time curves for the new relay under the following conditions: When a non-magnetic shim of correct thickness to give the longest certain action is added to a relay, curve 1 is described. That point at which the spring pressure overbalances the pull of the relay flux must not be beyond the knee of the curves, since there will

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not be sufficient change in total linkages with time to insure positive operation.

Without the shim, curve 2 is obtained. In this instance the rate of change is more gradual, since the inductance is greater. Also due to greater residual the entire curve is materially higher than 1, requiring a heavy spring pressure to overcome the magnetic pull.

If a negative flux, as shown by curve 3, is established by a second winding on this relay of sufficient strength merely to neutralize the residual of the iron, the resulting characteristic is illustrated by curve 4. The ratio of $L/r$ is high, giving a more gradual decay, and since no gap is present, comparatively few lines of force are necessary to hold in the armature, consequently making a small change an appreciable portion of the whole; that is, utilizing the slow but certain decay to the limit.

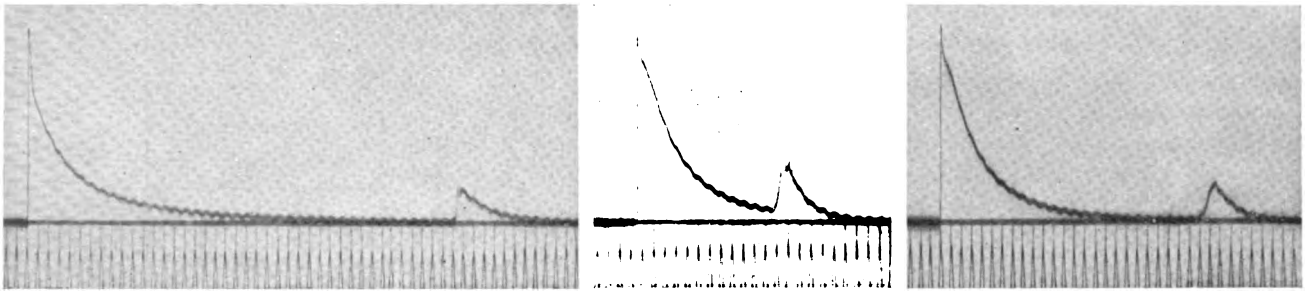
The increased flux at the left end of curve 3 results from transformer action when the main coil is deënergized, which temporarily reverses the neutralizing current. While this action is helpful it is not essential, for the necessary neutralizing coil is small

lograms taken to verify the above statements are shown in Fig. 10. In this particular set up, an exploring coil was placed around the iron circuit and the voltage recorded by the oscillograph element on the film was consequently proportional to the rate of change of the decaying flux. If these curves be integrated from a time $t = 0$ to $t = 10$ seconds, it is possible to obtain the approximate flux decay curves of Fig. 9.

Comparative data of the operation need not be taken from the calculated flux time curves but may be obtained directly from the rate of change of flux curves; i.e., the oscillograms.

It is evident from the above that the total possible time delay for a given relay with identical conditions of contact pressure and voltage may be increased greatly by utilization of the demagnetizing winding. When the longer times are not necessary, the kick out spring tension is increased and much better contact pressures result.

Another interesting characteristic is the inherently low voltage compensation. To reduce the number of spare parts which should be stocked, one coil only is



(a) (b) (c)

FIG. 10—OSCILLOGRAMS OF FLUX DECAY IN INDUCTIVE TIME-LIMIT RELAY

Film (a) was taken with normal voltage applied to both main and auxiliary windings; with moderate contact pressure the time delay was 1.7 seconds. When an air-gap shim, of such proportions as to insure maximum possible time with a certain operation was employed instead of the neutralizing winding, the drop out time was reduced to 0.52 seconds as shown by film (b), even though the identical relay, spring setting, and voltage were maintained. When the spring pressure was reduced to the point at which the armature would barely open, giving the maximum delay possible with the shimmed relay regardless of contact pressure, the time interval obtained, as shown by film (c) was 1.05 seconds.

in comparison to the main one in most applications,—the determining factors of course, being the retentivity of the magnetic circuit, and the most suitable rate at which it is desirable to demagnetize. These relays have been given some unusual applications and characteristics by proportioning these windings, and many possibilities have been discovered.

The drop out points $T_1$, and $T_2$ of the same relay operating on curves 1 and 4 of Fig. 9, are the limiting values. Any value of $t$ in between becomes available by merely changing the spring adjustment when curve 4 is employed. In no better way need the relays be compared, for it is seen that with a neutralizing winding, correctly proportioned, the residual can be reduced to approximately zero or even to a negative value, and that very good contact pressures are available in any but the longest settings.

Three of the most impressive of the many oscil-

employed, regardless of voltage, since there will be satisfactory operation from 300 to 30 or 40 volts, depending, of course, on the setting. The low applied voltages when the relay coils are placed across steps of starting resistance do not completely saturate the iron circuit. Hence a variation of line voltage appreciably affects a duplication of results. When a neutralizing winding is employed, the same variation of line voltage occurs in the auxiliary winding as in the main coil, affording partial compensation.

It will be seen from the above description of the TL relay that by purely electrical means, the necessity for a non-magnetic shim is eliminated, and with it the inconvenience of a change of calibration with continued armature pounding. No levers or hooks are necessary to hold the armature in place since stronger spring pressures give a sufficiently large upward force component. Unit construction has been developed so

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that even with the "make and break" electrical combination of contacts, the relay can be shipped to a customer as one piece.

### OPERATION

The application of the relays described can best be illustrated by a description of a typical time limit, plugging and reversing controller. Front and rear views of this control panel are shown at the beginning of the article and a schematic diagram in Fig. 11. The reversing contactors 1 and 3, 2 and 4, of diagram 14 operate in pairs and determine the direction of current flow through the armature and hence its direction of rotation, while 11, 12 and 13 short-circuit successive steps of starting resistance. Line contactor 5 insures complete protection in case of a grounded motor, resistors or brakes, and materially reduces the duty placed on the reversers, since the power circuit is broken in three instead of two places.

The polarizing coil of the *PR* relay is connected across the line and therefore sets up a main flux in a definite direction, while the movable coil is connected directly across the armature. When the master switch is placed in the forward position, the operating coils of 1, 3 and 5 and the forward contact of the *PR* relay are energized. These set up a power circuit through the motor and resistor, and the *RI* drop across the armature, impressed on the movable coil of the plugging relay causes it to make the forward contact as explained previously, thereby energizing the operating coil of contactor 11. At the instant of starting, the *RI* drop may have been only ten or fifteen volts depending, of course, upon the class of starting resistor and resistance of motor and motor leads. As the motor comes up to speed, however, the drop due to the counter e.m.f. generated by the motor rotation assists the armature resistance drop, making the total voltage across the armature very nearly equal to line voltage. It is for this reason that the *PR* relay had to be designed for so large an operating range.

The initial resistance drops between $R_1 - R_2$, and between $R_1 - R_3$ energized the main coils 12 and 13 of the TL relays, causing them to pick up and break their normally closed contacts. With the closure of contactor 11, however, the step $R_1 - R_2$ of resistance is short-circuited, and the voltage across the main winding 12 *M* of the relay is reduced to zero. The starting resistor acts as a discharge, and the flux decay in the relay circuit, assisted by the action of the neutralizing winding, approaches a value at which its holding power is overbalanced by the kick-out spring pressure. In a predetermined time the relay drops open, closing contacts 12 *R*, which in turn cause contactor 12 to close. The closure of contactor 12 short-circuits the $R_2 - R_3$ step of resistance and the same relay action is repeated, so that in a definite time accelerator contact 13 is closed, placing the motor across the line.

When the motor is plugged by throwing the master switch from forward to full speed reverse, all the contactors drop out and immediately 2, 4 and 5 close again. Regardless of whether the motor is series, shunt or compound, the counter e.m.f. drop will remain in the same direction as long as the motor is rotating forward, since the direction of the field has not been changed, even though the line current through the armature is now reversed. Power is fed from the reverse contact of the master switch to the reverse contact of the plugging relay, but as long as the counter e.m.f. drop corresponding to the forward rotation of the motor overbalances the RI drop, which now is opposing the plugging relay, will continue to make its forward contact, and thereby prevent contactor 11 from short-circuiting the plugging step of resistance.

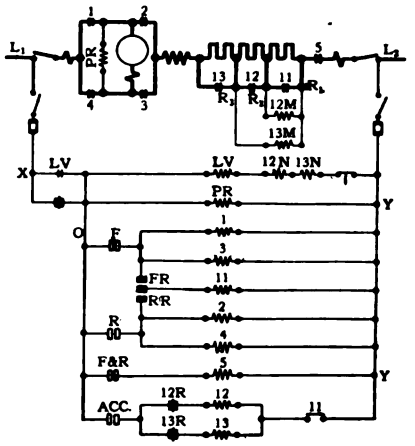


FIG. 11—SCHEMATIC DIAGRAM OF TIME LIMIT, PLUGGING AND REVERSING CONTROLLER, ILLUSTRATED AT THE BEGINNING OF THE ARTICLE

When the motor has come practically to a standstill, the PR relay makes its reverse contact, contactor 11 closes and 12 and 13 will follow in predetermined times as previously described.

The relay and control schemes described seem to offer a complete solution to the problems of controlling electric motors for heavy mill service, as they will permit a motor to start any load which it is capable of breaking away from the initial condition of exceptional high friction, without in any way interferring with its subsequent normal operation. The description of the time limit and plugging relays which are the fundamental links in this new solution of an old problem, and the description of the operation of a plugging reversing controller show clearly the simplicity of application, ease of adjustment, and freedom from variations with mill operating conditions. An even more forcible example of their ease of application is to be found in the operation of a crane hoist controller, but sufficient room is not available here for such an explanation.

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# Changing from Cast Iron and Steel to Fabricated Steel

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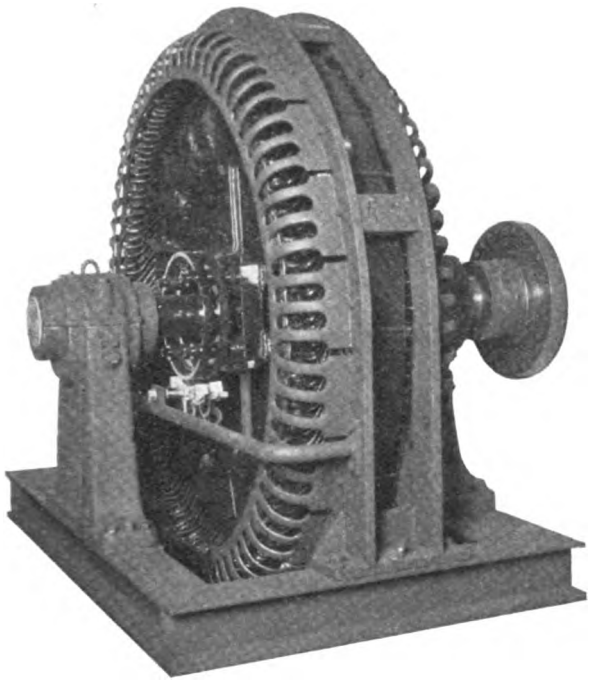
Westinghouse Electric & Mfg. Co.



A TYPICAL 600 HP, 100 PERCENT POWER-FACTOR, THREE-PHASE, 60 CYCLE SYNCHRONOUS MOTOR

A ROTOR FOR A 300 HP, 225 R.P.M. THREE-PHASE, 60 CYCLE SYNCHRONOUS MOTOR

The only castings used in these motors are those of the bearings and pedestals. Segments cut by automatic gas-cutting machines from a steel plate, bent to shape and butt welded together form the stator. The end bells are made from steel stampings. The new method of holding the laminations can be seen here. No cast iron is used in the rotor. The arms are made by arc welding together H-beams, welded to the hub which is cut from heavy steel plates.

THE substitution of punched, pressed and rolled steel for castings, which has been increasing in importance for many years in the electrical industry, has been supplemented by the further substitution of fabricated (usually arc-welded) structural steel instead of castings for the largest and most complicated frames, bedplates, etc., until castings bid fair to be a rarity in the no distant future. This is not a new idea; rolled steel motor frames have been common for sixteen years or more*, ante-dating even the use of electric arc welding with the metallic electrode. But the general application of fabricated steel in place of castings in the construction of the larger rotating machinery is relatively new, and the change is not even yet completed. This change is the result of a number of different factors.

The big advantage of this type of construction lies in the fact that complicated parts can be made up in much less time than is required for the making of a pattern and casting; using steel shapes which are the standard product of steel mills. To realize on the possibilities of this method of manufacture, it is necessary to carry a large and varied stock of standard shapes, bars, slabs, plates, etc. The selection of the kinds and amounts of such stocks requires a careful study of the activity of the various types of structures that are to be fabricated, as well as the equipment and manufacturing methods to be used. By careful administration of the application of the stock, scrap ratios can be kept within reasonable limits, but it is essential that a careful layout be made of the stock size in each application.

The machining of a casting is a longer and more costly operation than that of rolled steel parts, because of the excess stock which must be added to a casting to insure that the machined parts will clean up. In addition, the chilled scale, sand and hard spots that are encountered on the surface of a casting slow up the speeds and reduce the feeds to a great extent, and also cause considerable tool breakages. The inevitable losses that occur from defects, which are not found in a great many cases until the machining is practically finished, form another frequent source of delay and extra cost. The use of fabricated steel parts, therefore, makes it possible to reduce the machining time considerably, as well as to eliminate certain ma-

*See article on "Progress in Motor Manufacture" by C. W. Starker in the JOURNAL for March 1913, p. 199.

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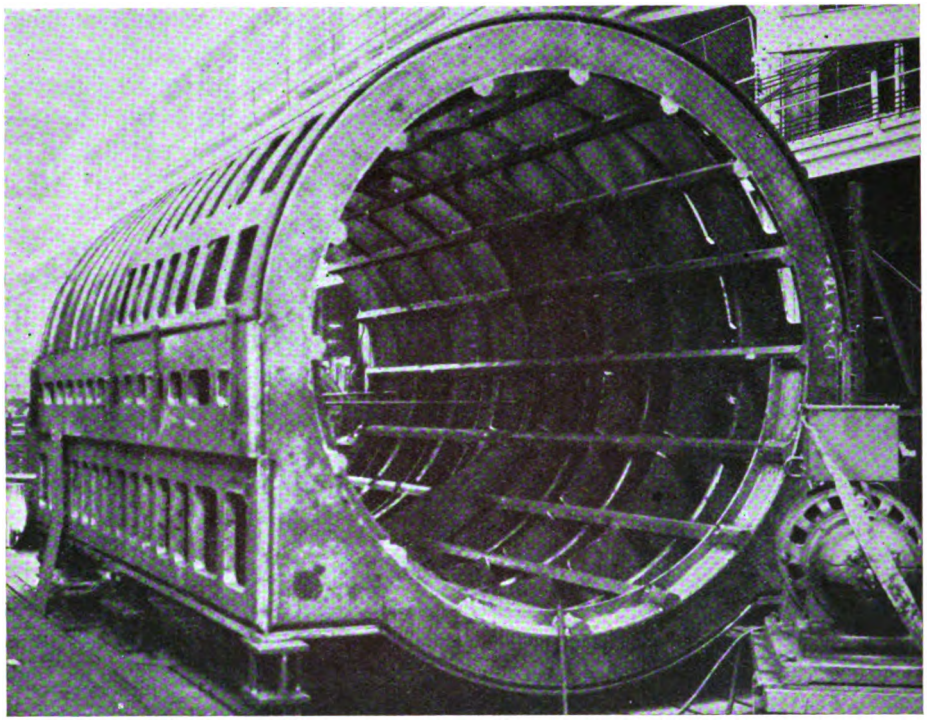


AN ALL WELDED STATOR FOR A 94 200 KV-A TURBOGENERATOR

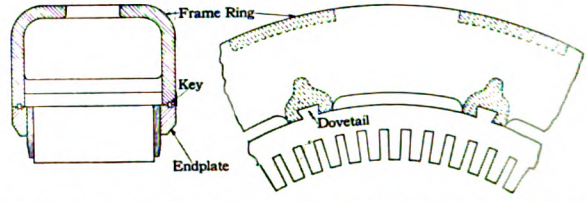
This stator is 220 in. long and is made by fastening together rings cut from steel plate with automatic gas-cutting machines. The rings are held together on the inside by axial bars welded in place, and on the outside by steel plate bent to shape and welded on. The supports for the frame feet are also made from steel plate. The laminations will be slipped on round rods welded to the axial bars in the core. Pressure will be applied to the laminations by nuts on each end of the bars, bearing down on the end plates. The only machining consisted of a light bore cut on the axial bars to which the lamination rods are to be welded and some machining on the plates to which are bolted the feet. The feet are made removable to meet railroad clearances. Otherwise the stator will be shipped completely assembled.

to meet certain definite requirements. Some details of the two types of construction are shown in the accompanying sketches.

The cast frame is of the box-type construction, having the laminated core held in place by dovetails and clamped between two end plates which are keyed in position after the core is stacked. The cast frame is machined at the bore and on the sides. In addition another set-up is required on a different machine to cut the dovetails. Besides this, the two end plates, which are slender castings and difficult to make, are machined on all sides.

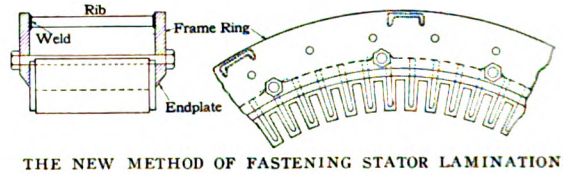
The fabricated frame consists simply of two frame rings gas-cut from a solid plate with the core held in place between the rings by frame bolts, which also serve as a means of properly tightening the core. Between the frame rings at the back are welded ribs of channel iron which give rigidity to the structure and serve as a means of lifting. Note the simplicity of the construction. There is no boring mill or milling machine work anywhere on the frame. Nothing but a gas torch, arc welder and drill press are used in making the frames. Even the bottoms of the frame feet are not machined and yet the structure fulfills all the requirements. It would have been easy to fabricate a box-type frame, use fabricated end plates, machine the frame and assemble it in the usual way, making it look like the cast frame. This is the result where the designer thinks in terms of cast iron and orders fabricated steel in his bill of material. It is not the kind of design produced when the designer says "These are the requirements of my structure. Here are the fabricated materials to be used. How can they be utilized in the simplest manner to fulfill these requirements?" With this attitude of mind engineers produce designs which capitalize to the fullest extent the possibilities of fabricated steel.

The general suitability of the design to structural materials is an important point which is often overlooked. Structural materials are partially finished materials, and to be suitable for their use a design should be so made as to use the rolled surfaces of the plates and bars as finished surfaces in the completed structure. This means that much of the machine




THE METHOD OF FASTENING STATOR LAMINATIONS IN A CAST-IRON FRAME

With this construction it is necessary to machine the surface of the frame ribs and cut in them the dovetail slots for the laminations.




THE NEW METHOD OF FASTENING STATOR LAMINATIONS

The laminations do not have the customary dovetails but have holes stamped in their edges. Thus more laminations can be punched from a given sheet. The laminations are slipped over round rods, pressure being applied by nuts on the outside of the end plates. No machining is necessary.

work required on cast structures can be eliminated when the fabricated construction is used—provided the design is properly made.

Another point of interest in this frame construction is the fact that it is entirely open in the back. This is, to say the least, a radical departure from the

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cast frame, but why not depart? The plate on the back is unnecessary for strength, except in very wide machines, and by leaving it open the ventilation is much improved. Something is gained and nothing lost. Of course, if the object were to make a frame look like a cast frame, a plate would be put on the back, but it was agreed to approach this design problem with an open mind, forgetting cast construction altogether, with a view to producing the simplest frame construction. Putting the plate on the back makes a poorer design and one which is more expensive.

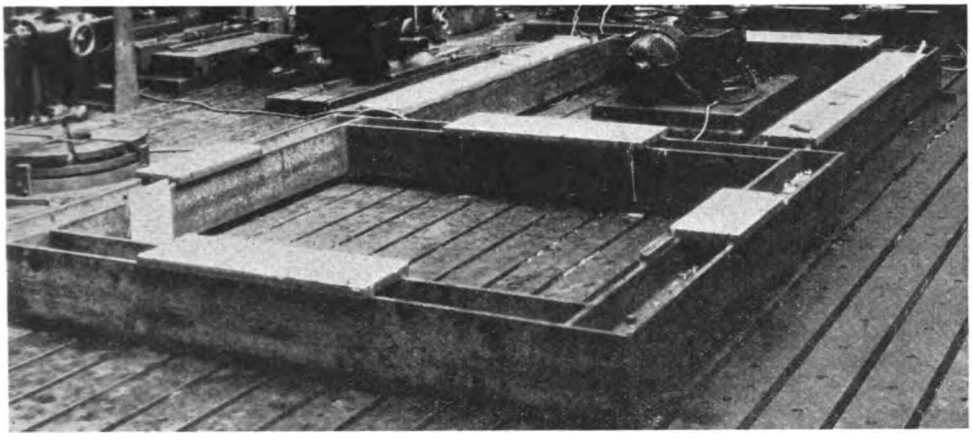
It was with the same object—of obtaining a design especially suited to fabricated steel—that it was decided to stack the punchings on bolts. The bolt is obviously more suitable to the fabricated construction. To cut dovetails in cast iron is an expensive operation, but to cut them in ribs of rolled steel is still more difficult and expensive. Yet there was a good deal of apprehension about the use of bolts. The location of the holes drilled in the frame rings is depended on entirely to make the core round, and doubt was expressed as to how nearly round it would be. It was also felt that trouble might be experienced in getting the core to stack up straight and square. But the bolt was felt to be the only construction suited to fabricated steel, and hence it was tried out thoroughly in the narrow core machines, possibly up to 10 inches wide. Today, after two and one-half years experience, the largest turbogenerator in the world is built in a fabricated frame with the core stacked on bolts. It has a core of 220 inches.

The point to be gained from this frame illustration is that if designs in structural steel are to be successful, the design problems must be approached with open and unprejudiced minds, forgetting both the general construction and appearance of cast structures. By doing this, the designs will be suitable to structural materials. They will be simpler than cast designs and will have less machining, because they will make use of the fact that structural materials are already partially finished.

Now it may be that this same attitude of open-mindedness on the part of the design engineer may cause considerable distress to the sales department. While actually it is economically sound, practically it may produce structures which are so radically different in appearance from the cast structures he is accustomed to, that the salesman throws up his hands and wants to know how in the world he is expected to sell machines so radical in appearance.

Experience has shown the answer to this problem. When fabricated bedplates were first made of H-beams, they were considered ugly. But that did not last long. The fabricated bedplates were better than the cast ones. And today the same people who once thought they looked so terrible will tell you they are actually better-looking than the cast bedplates.

We didn't change the looks, but we did find that



A BEDPLATE FOR A STEEL MILL MOTOR-GENERATOR SET

The construction here is slightly different from that previous shown in that the H-beams are laid with the flanges vertical. The pads welded to the flanges support the pedestals and motor frames.

A FABRICATED SURFACE PLATE FOR SHOP MACHINING

This type of plate is used for clamping and holding structures for fabricating and welding together and replaces the cast iron plates previously used. This plate is made from standard I-beams and rolled plate.

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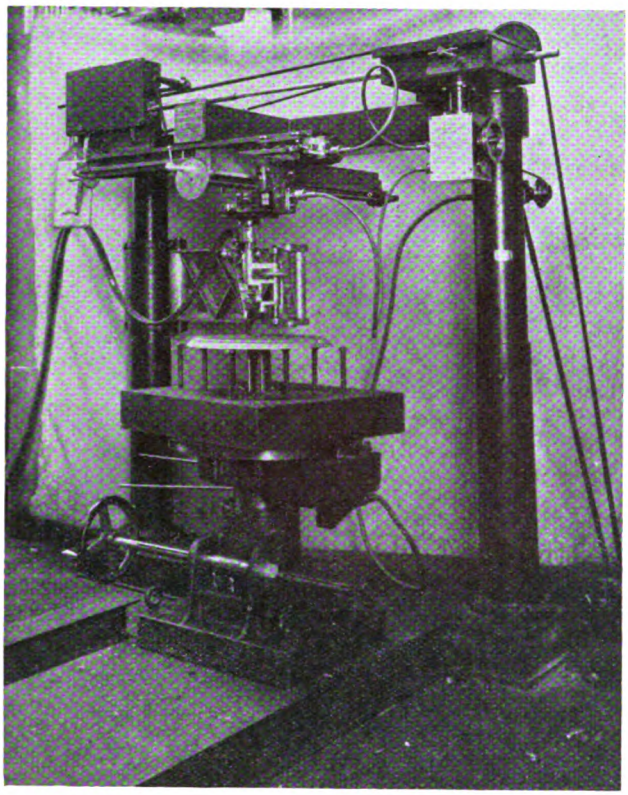
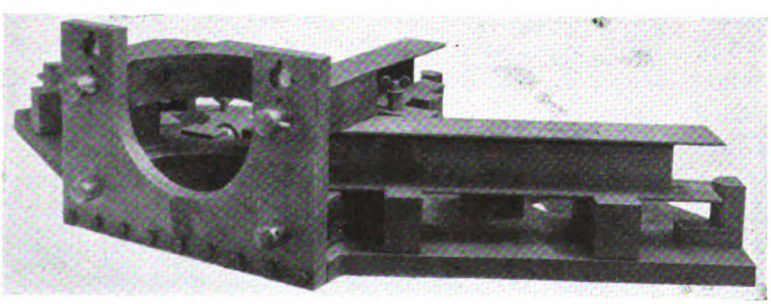
an old principle applies—that what looks good is simply a matter of what we are used to looking at. If we are accustomed to looking at cast structures, they look best. If we are in the habit of looking at fabricated structures, they look best. What is radical today is commonplace tomorrow.



GAS-CUTTING MACHINE FOR CUTTING STEEL PLATE

This machine can cut plate from ½ to 8 in. in thickness, either from compound or simple templates; or without a template by using a motor-driven table and power feed. The surfaces made by these cutting machines are smooth and true, and accurate to within 1/16 in.

Now, if this principle is true—that appearance is not an intrinsic quality of the design, but simply a matter of what one is used to—there is another principle which follows from it as a corollary. It is this. We cannot justify from an economic standpoint, the expenditure of a single cent to make a design "good-looking." We must not do machine-work unless it is necessary. We must not add plates or put in holes just to make a structure look like a cast structure. It is not sound engineering. In the long run, that machine will both look best, and sell best, which is most closely and simply adapted to the purpose for which it was designed.



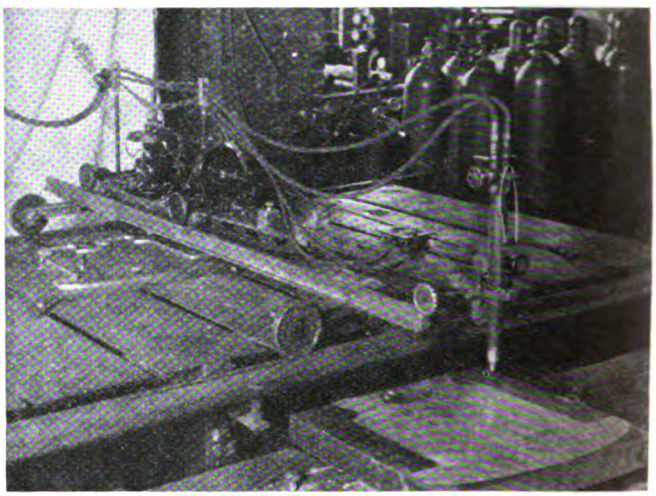
A WELDING FIXTURE FOR USE IN FABRICATING ROTORS

The H-beams for the arms and the steel plate hubs are held in place, properly spaced and true to each other during the welding process. It is unnecessary to make any heavy machine cuts after welding.

### THE LIMITATIONS OF FABRICATED STEEL CONSTRUCTION

There seem to be two classes of structures for which a fabricated steel construction cannot be justified. First, small structures of high activity. Examples are the frames and brackets of small diameter machines, like induction motors and general-purpose synchronous motors. Here metal patterns are used with automatic moulding, and the machining operations are done by automatic machines of the highest development. Castings are cheap, machining is cheap, and the fabricated steel construction invariably proves more expensive.

The second example is the case of structures of such peculiar shapes that they are not readily made out of the commercial shapes of steel, such as bars, beams and plates. Pedestal bearings are a good example. Many attempts have been made to fabricate bearing pedestals, but so far it cannot be done at a cost comparable with cast pedestals. Some pedestals have been made for anti-friction bearings and some for sleeve bearings, but there are so many little pieces, and so much welding is required, and there seems to be almost no saving in the machine-work due to the use of the fabricated steel, so that the cost is always excessive. But here again, a more courageous abandonment of preconceived ideas of what pedestals should look like may change this situation.



ANOTHER TYPE OF GAS-CUTTING MACHINE

This machine cuts plates from ½ to about 8 in. in thickness, either by means of templates or the straight line process, requiring control of the motor-driven feed.

### CONCLUSION

In any fabricated steel program, it is usually difficult to show any great saving over a good cast design when made with good

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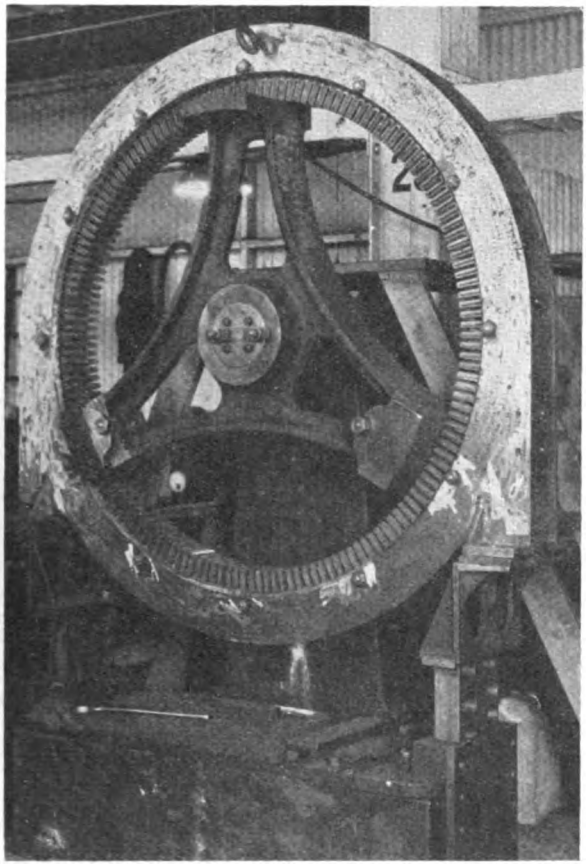
foundry equipment and machined on modern machine tools. It is felt, however, that even at the same cost, the use of fabricated steel is justified for the following reasons:—

1—The possibilities of future cost reduction are greater, because the fabrication of steel is a comparatively new art, while the cost reduction possibilities of the cast construction may have been largely exploited.

2—The fabricated steel design is flexible. A large number of different structures can be made from a limited number of parts by welding them together in different combinations—also, minor changes are easily made. Greater strength can be obtained by adding additional members to a design made up originally for lighter service. These are some of the things which make the design flexible.

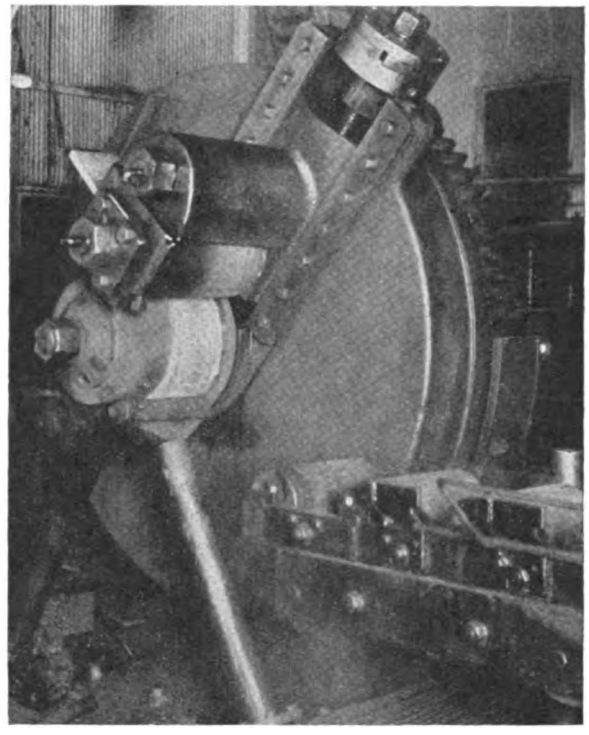


A STATOR WELDING FIXTURE

Used to hold the frames true to the bore while the feet are being welded, thus insuring that they are square and true to the center of the frame. It is therefore unnecessary to do any machining on the feet. All preliminary drilling and machining is done previous to the welding operation.

3—The elimination of patterns is a clear gain. This is of greatest value in large, special machines where only a single unit is made. Also, most large bedplates are special. There are very few exact duplicates, and with castings, patterns are continually being changed.

4—Shorter deliveries are possible with the steel construction. With the foundry and the pattern problem out of the picture, a shorter and more direct manufacturing sequence is possible. In fact, the whole process can be done in the same shop. Greater concentration of responsibility in the manufacturing organization can be had and this means greater efficiency and quicker production.



AN EARLY FRAME BENDING EQUIPMENT

This was installed in the East Pittsburgh factory in 1909 and has been in use continuously in making frames for small direct-current motors from steel plate. The hot plates are brought from the furnace on the transfer table at the right, placed on the proper size mandrel and rolled to shape. A frame partially rolled can be seen on the mandrel, the unrolled end projecting beyond on the far side. The bores of these frames are accurate to less than 1/16 in.

5—Fabricated steel structures are often better structures than were the cast. There are many sales arguments to be advanced in their favor and they are being demanded more and more by the public.

These are some of the principal reasons why the fabricated steel construction is being adopted for large power apparatus—including engine and coupled type synchronous motors and generators; vertical water wheel generators; high-speed and low-speed direct-current generators and converters; all bedplates; and, finally, turbogenerator frames and bases.

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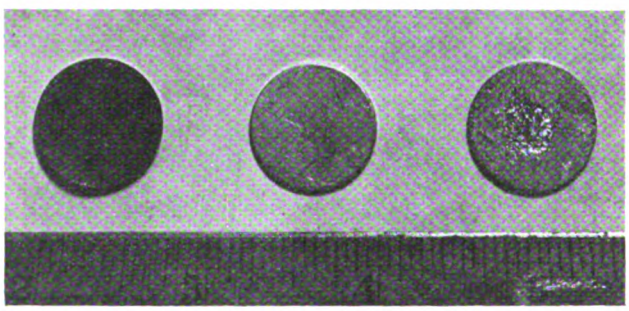
# Low Voltage Cutouts

## For Series Street-Lighting Transformers

E. J. HAVERSTICK
Research Laboratory,
Westinghouse Electric & Mfg. Co.

THE elimination of telephone interference from series street-lighting circuits is an old problem, having come into existence early in the development of the telephone and power industries. A particular cause of interference is the operating of series transformers with open secondaries after lamp failure in lighting circuits using high current, high candle-power lamps with individual series transformers. Complaints of interference with radio reception are also received as being due to the same cause.

As is well known, when a street-lighting series transformer is operated with the secondary open, harmonic voltages develop, the peak of the voltage wave being about five to eight times the r.m.s. normal operating voltage. The effect of such harmonic voltages upon neighboring telephone circuits has been previously pointed out*. In order to eliminate this interference effectively some means must be used to prevent the development of these harmonic voltages. To do this a new cutout has been developed which short-circuits the secondary of the transformer following the lamp failure.



(c) (b) (a)

FIG. 1—APPEARANCE OF LOW VOLTAGE CUTOUTS

(a) Aluminum powder type; (b) cover for either type; (c) conducting coat type.

### REQUIREMENTS FOR A SATISFACTORY CUTOUT

Any device used to prevent the development of the harmonic voltages must meet certain general requirements and in addition, certain particular requirements which depend entirely on the type of device.

*The Cutout Must Be Small* enough to be used in the present standard socket and also to permit easy replacement at the time of lamp renewal.

*The Cutout Must Not Operate on Normal Lamp Voltage*—In fact it must not operate at a voltage somewhat higher than the normal lamp voltage in order to take care of slight variations in the supply, yet it must respond quickly on a voltage somewhat below the peak value of the open-circuit voltage.

*The Cutout Must withstand Fairly High Temperature*—Since the cutout, for convenience, is held by springs attached to the lamp socket and thus extends up into the lamp housing, the cutout must not be altered or have its characteristics changed due to the temperature reached in the lamp housing.

*The Cutout Must Operate Quickly*—Upon failure of a lamp, the cutout must short-circuit the transformer secondary in, at most, only a few cycles of 60 cycle current.

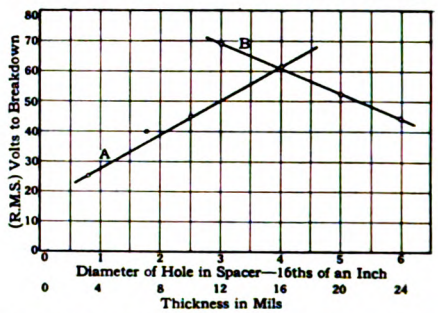



FIG. 2—APPROXIMATE MEAN VALUE OF BREAK-DOWN RANGE

*A*—Change of break-down voltage with thickness of spacer with 1/4 in. diameter hole in spacer. *B*—Change of break-down voltage with diameter of hole in a 16 mil spacer

*The Action of the Cutout Must Be Positive*—that is, it must form a conducting path which is able to carry the short-circuit current, and not open again by burning out or after the circuit is de-energized.

*The Cost Must Be Relatively Low*—The cost of replacements must be kept small enough that the advantages gained by the use of series transformers are not offset by the maintenance cost.

### FORM OF CUTOUT

Such a short-circuiting device may consist of a resistance material against which a contact is made.

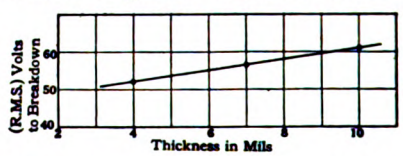



FIG. 3—AVERAGE INCREASE IN BREAK-DOWN VOLTAGE WITH INCREASE IN THICKNESS OF SPACER

When the voltage across the contact increases, the leakage current also increases. Due to negative temperature characteristics the leakage current increases with temperature as well as voltage until the temperature of the resistance material reaches the point where breakdown occurs. The breakdown results from a change in the character of the material or by the fusion

*By McCurdy in his paper on "Induction from Street Lighting Circuits" in the *Jour. A. I. E. E.*, Oct. 1925.

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of imbedded or attached low melting-point metals or alloys.

A device of this type requires an appreciable time to bring about the required change in the character of the material or the fusion of the low melting point metal or alloy, and therefore it has little value for the service required. In addition, the size is likely to be too great to permit installation in the standard manner,

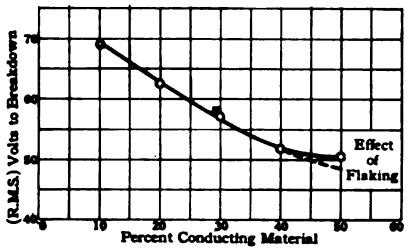



FIG. 4—EFFECT OF PERCENTAGE OF CONDUCTING MATERIAL IN THE COATING ON BREAK-DOWN VOLTAGE

and there is also a possibility of re-opening due to destruction of the conducting medium.

The low voltage cutout just developed is not susceptible to these troubles and much more adequately satisfies the requirements of a good cutout. Two forms in which this cutout is made are shown in Fig. 1. Both of these satisfy the condition of limited size, as they are only ¾ in. in diameter and approximately 60 mils thick, the thickness varying slightly for different breakdown ranges.

The cutout at (a) takes advantage of the high resistance of conducting materials when in a finely divided state. Finely divided aluminum has this property to a pronounced degree, and is used as a filler in the space between two electrodes separated by an annular ring of insulating material several mils thick. At normal lamp voltage the resistance of the aluminum particles is so high that there is no leakage. Upon increasing the voltage across the cutout, though, a point is reached at which the resistance suddenly disappears and if sufficient power is available a permanent, con-

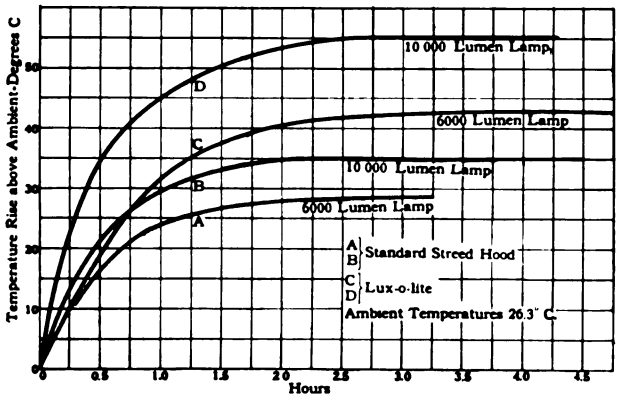


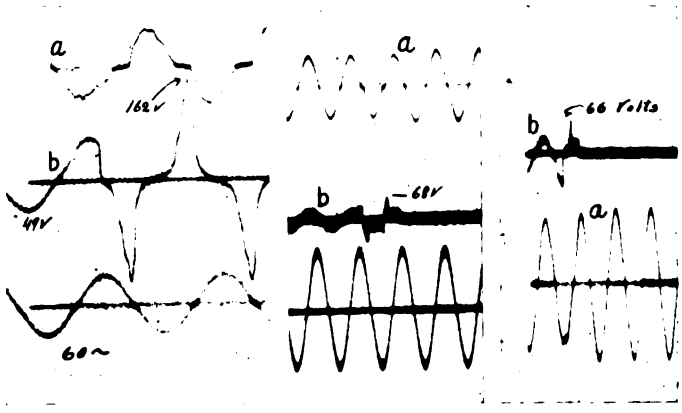

FIG. 5—TEMPERATURE RISE AT CUTOUT IN LUX-O-LITE AND STANDARD STREET HOOD UNITS

ducting path of fused material is formed between the two electrodes.

Tests made on thousands of such cutouts show that with a given thickness of spacer and size of the annular ring, a narrow range of breakdown can be arranged. A means of control is thus attained by changing either the thickness of the spacer or the size of the annular ring. The variations of breakdown voltage with spacer thickness and electrode area covered are given in the curves of Fig. 2.

The cutout shown at (c) Fig. 1 differs slightly in form from the aluminum powder type. A small hole is punched in the spacers separating the electrodes and one side of the spacer is coated with a conducting powder suspended in a liquid. The edges of the hole in the spacer are also coated, thus forming a leakage path along which flashover occurs when the voltage impressed upon the cutout reaches a sufficiently high value. The electrodes are made of aluminum as in the first cutout. When flashover occurs the electrodes are welded together and a permanent, conducting path is thus formed.

In this cutout, control of the breakdown range is obtained by changing the thickness of the separator, and also by changing the concentration of the conducting material in the coating suspension. This is shown




FIGS. 6, 7 AND 8—OSCILLOGRAMS REPRESENTING THE SHORT TIME OF OPERATION OF THE NEW CUTOUT

Curve *a* represents the current in the primary and curve *b* the voltage across the secondary of a series street-lighting transformer. In Fig. 6 is shown the distorted wave form which results from an open secondary, with values of peak voltage before and after the secondary was opened. Figs. 7 and 8 show the rate at which the cutouts operate when the lamp circuit is opened and the secondary voltage begins to rise; Fig. 7 representing the aluminum powder type and Fig. 8 the conducting coat type. These oscillograms both show that the cutout functions so quickly that the secondary voltage does not approach the high peak value reached when it is open circuited, as shown in Fig. 6. Even when the delay is a few cycles, the open-circuit values are not attained.

in Figs. 3 and 4, which give the variation in breakdown voltage with thickness of the spacer, and also with the change in concentration of the conducting material in the coating suspension. This cutout can be made for lamps having higher operating voltages than the first type, and has another advantage in that the manufacturing processes can be made practically continuous.

These cutouts have been developed for use with lamps having normal operating voltages from 10 to 26.5 r.m.s. volts, that is, for lamps of from 1000 to

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10 000 lumens. The open-circuit voltage peaks cover a range from 127 to 164 volts.

LAMP HOUSING TEMPERATURE

The cutouts in service are mounted in the lamp housing. The temperatures to which they are likely to be subjected are shown in the curves of Fig. 5, which give the temperature attained when 6000 and 10 000 lumen lamps are used in a standard Street Hood and a standard Lux-o-lite unit. Numerous tests have shown that the cutouts as developed are satisfactory at these temperatures.

EFFECT OF RADIATED DISCHARGE

Numerous tests made in the laboratory by subjecting the cutouts to a radiated discharge from a condenser test set charged to 20 kv indicated that the cutouts would not respond to electrical storms. During a very severe storm in one district in which service tests were conducted a number of the cutouts failed. All of those failing, with but one exception, had been in service for 60 days. Despite this seemingly poor service from the protective device, the power company was well pleased, because by the short-circuiting of the cutouts they reduced to practically zero the lamp failures which usually accompany storms of the magnitude experienced.

In discussing lighting installations using individual series transformers, McCurdy* says "the most direct and fundamental remedy for interference of this type of circuit would be the provision in each fixture of a device which would short-circuit the individual transformer when the associated lamp fails". The cutouts described in this paper satisfactorily meet the existing need for such a device, as they are small in size, they can be be made for various voltage ranges, and they function quickly and positively.

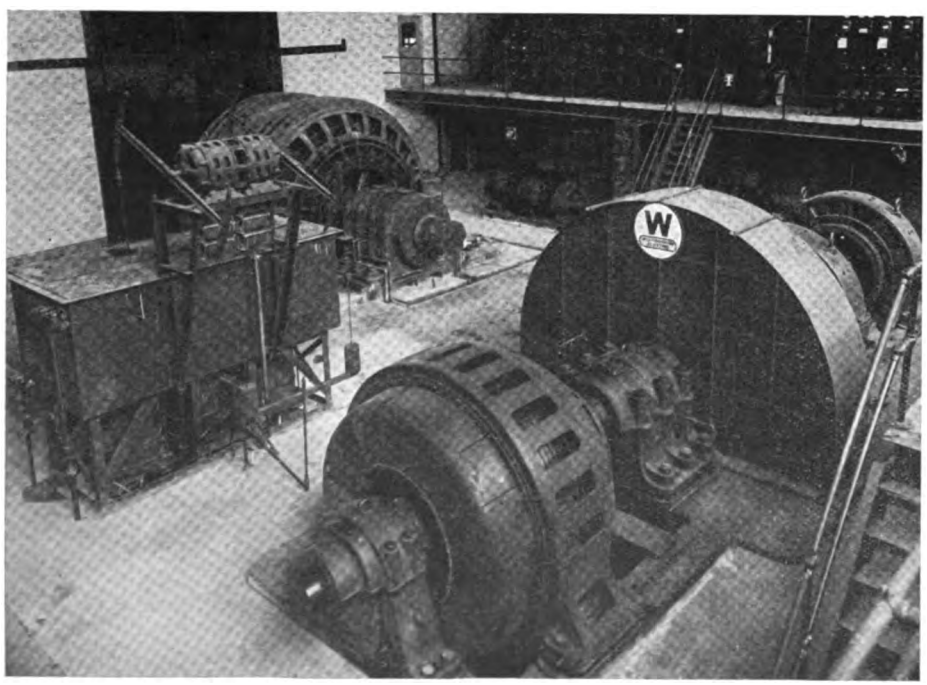
*loc. cit.

# The Wound-Rotor Induction Motor

## Its Performance and Operation at Reduced Speeds

R. R. SHEELY
Industrial Motor Engr. Dept.,
Westinghouse Electric & Mfg. Co.

THE energy transferred across the air-gap of the induction motor may be divided into mechanical and electrical components. The mechanical component consists of two parts. The first represents the shaft output, assumed to be fixed by the requirements of the connected apparatus; and the second is the friction loss of the motor, which is determined largely by the type and condition of bearings and the type and arrangement of fan, ventilating ducts and general design of the rotor. When the motor is operated below normal speed the electrical component may be divided into the resistance loss in the secondary winding, which is determined when the motor is designed; and the energy transferred to the control apparatus. As a general rule, this is absorbed in resistance grids and wasted. Various schemes have been devised to utilize this energy by conversion to direct current or line frequency alternating current, but these are mentioned here only as a matter of interest, as this discussion is to be confined to the use of resistance for speed control.



REVERSING MILL MOTOR WITH FLYWHEEL MOTOR-GENERATOR SET AND SLIP REGULATOR

The reversing mill motor in the background at the left is driven by the flywheel motor-generator set on the right. This is in turn controlled by the slip regulator located in left foreground.

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The simplest form of control is designed for occasional starting from rest, for continuous operation at constant motor speed. In this case, the energy loss in the control is of little importance, except to the designer in selecting suitable switches and resistance grids.

The next step is necessary where frequent starting and stopping is required, as on elevators and hoists, where a large part of the operating cycle is spent in accelerating the load. In cases where quick stops are

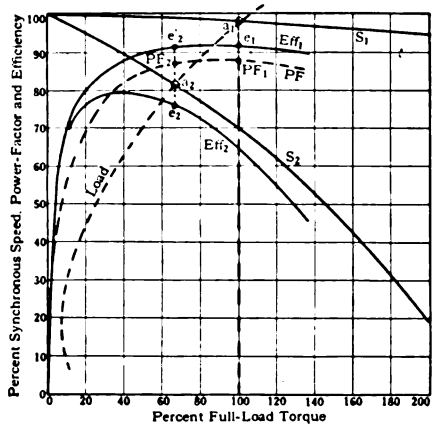


FIG. 1—RELATION OF SPEED, EFFICIENCY AND POWER-FACTOR TO TORQUE WITH DIFFERENT ROTOR RESISTANCES

necessary the primary of the motor may be reversed or plugged with the proper value of resistance in the secondary circuit to give the maximum torque. A variation of this practice is sometimes used by impressing suitable direct-current voltage across one or two phases of the primary.

On various fan and centrifugal pump drives it is sometimes desirable to operate at reduced speed for considerable periods of time. In these cases a careful analysis of the effects of such operation on the performance of the motor is desirable. The wound-rotor induction motor is well suited to this type of drive, since the power required decreases rapidly with decreasing speed, and the loss in the resistance grids is of little importance.

The ratio of mechanical and electrical components of the rotor output mentioned above is determined by the ratio of the operating speed $S_2$ to the normal speed $S_1$ (rotor short-circuited) for the same torque. Since the electrical output is assumed to be lost in the control resistance, the overall efficiency $E_2$ of the motor and control is expressed by the equation:—

$$E_2 = E_1 S_2/S_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where $E_1$ represents the efficiency for the conditions given for $S_1$ and is determined from the normal characteristic curves of the motor. $S_1$ and $S_2$ are sometimes expressed in terms of slip as follows:—

$$\frac{S_2}{S_1} = \frac{(100 - s_2)}{(100 - s_1)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where $s_1$ and $s_2$ represent the percent difference between actual and synchronous (approximately no-load) speed.

If the above efficiency equation is used to check the motor for several speeds, at constant torque it will be found that the energy input to the primary remains constant. In a like manner, it can be proved that the reactance component also remains constant, with the result that the power-factor of the primary current is found to depend only on the torque at which the motor is operating.

Several curves of speed, efficiency and power-factor for different values of secondary resistance, plotted against torque as the abscissae, are shown in Fig. 1. It will be noticed that separate speed-torque and efficiency-torque curves are required for each value of resistance, but one power-factor curve serves for all combinations. $Eff_1$ and $S_1$ are normal efficiency and speed-torque curves with secondary short-circuited. $Eff_2$ and $S_2$ are efficiency and speed-torque curves for the first step of resistance.

A typical speed-torque curve for a fan has also been drawn in Fig. 1 as a representative load. The points $a_1$ and $a_2$ represent the speeds at which the combination would operate under the above conditions, with $e_1$ and $e_2$ representing the efficiencies and $PF_1$ and $PF_2$ representing the power-factors for the respective speeds. In actual practice the efficiency for point $a_2$ would be determined by projecting to $e_2'$ on the No. 1 efficiency curve, and the actual efficiency calculated by equation (1).

An interesting point illustrated when speed and efficiency-torque curves are plotted to a percentage scale is that the speed for any torque gives the efficiency of the secondary circuit, and the percent difference between the efficiency and speed curves represents the primary loss. Thus the overall efficiency, which is the product of the primary and secondary efficiencies, will always be below the speed-torque curve for any value of secondary resistance.

From these curves it will be seen that very great speed reductions are undesirable on account of the low efficiency. This, combined with the poor speed regulation and reduced cooling, tend to limit the minimum speed to approximately 50 percent of normal.

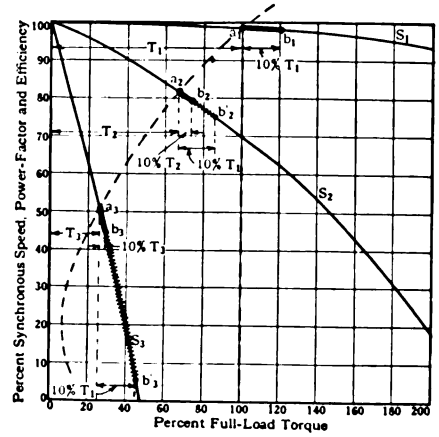


FIG. 2—SPEED REGULATION WITH DIFFERENT VALUES OF RESISTANCE

The curves in Fig. 2, on which $T_1$, $T_2$ and $T_3$ represent the torques required at points $a_1$, $a_2$ and $a_3$

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respectively, illustrate the change in speed regulation for different values of secondary resistance. For a ten percent increase in torque on curve $S_1$ ($a_1$ to $b_1$) the speed reduction is less than one percent. By referring to curve $S_3$, however, it will be seen that the same percentage change in torque ($a_3$ to $b_3$) gives approximately 12 percent reduction in speed. If the foot-pounds change in torque is the same for both curves ($a_3$ to $b_3'$ for $S_3$) the reduction in speed for $S_3$ is approximately 90 percent. The corresponding values of torque and speed are indicated on $S_2$ for an intermediate step of resistance for general reference. For some applications this condition tends to produce instability and hunting.

The cooling effect of the motor fans and ventilating ducts is decreased at reduced speeds, with a corresponding increase in temperature rise above that obtained with the same torque at normal speed. In most cases where continuous operation at reduced speed is encountered, the torque required by the load decreases rapidly with decreased speed, so that the safe temperature permitted by the insulation is not exceeded. The actual temperature rise encountered at reduced speeds and torques depends to a large extent on the ratio of variable to constant losses in the machine. This condition prevents the use of any except very approximate means of predetermining the temperature rise.

The curves shown in Fig. 3 were determined from tests on several motors. Curve *ST* 40° represents the speed-torque curve of the motor for continuous operation at 40 degrees C. temperature rise. The fan curve is the same as used in Figs. 1 and 2. From the comparison of these two curves, it will be seen that the torque required to drive the fan at 50 percent speed

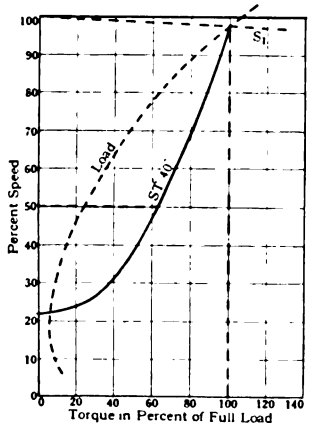


FIG. 3—SPEED-TORQUE CURVE CORRESPONDING TO 40 DEGREES C. TEMPERATURE RISE

is only 25 percent of the full-load torque, while the motor is capable of operating continuously at more than 60 percent torque. Thus the temperature rise of the motor when driving the fan will be less than 40 degrees C. In any case where the torque required at half speed exceeds 60 percent of full-load torque, a suitable safety factor should be applied to determine the nominal motor rating.

In some cases where the power demand of the load fluctuates rapidly, as in rolling mill, hoist or welding service, it is desirable to use a flywheel to store

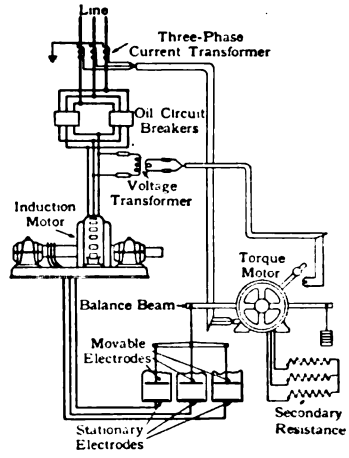


FIG. 4—SCHEMATIC DIAGRAM OF INDUCTION MOTOR WITH LIQUID SLIP REGULATOR

up energy between peak loads. In order to take advantage of the energy stored in the flywheel as the load increases, it is desirable to have a greater decrease in speed than that obtained with the secondary short-circuited. This may be accomplished by inserting a suitable resistance in the secondary circuit. Thus when the load is very small the motor will tend to bring the flywheel up to approximately synchronous speed. As the peak load is applied, however, the flywheel will be forced to slow down and give up a part of its stored energy. If the motor secondary was short-circuited, a drop of two to three percent in flywheel speed would produce full-load torque on the motor, but with the proper value of external resistance it is possible to utilize a much larger portion of the stored energy of the flywheel.

This external resistance may be a fixed amount to give a slip of say 10 to 15 percent at full-load torque, or a liquid rheostat and torque motor, known as a slip regulator, may be arranged as shown in Fig. 4, so that when the motor load increases to a predetermined point the secondary resistance is automatically increased to allow a further decrease in speed without excessive overload on the motor.

Either form of secondary control, when using a flywheel, gives a considerable decrease in peak loads on the power system on some applications, thus permitting the use of a smaller driving motor, more favorable rates for purchasing power and the reduction of overloads to safe limits where the capacity of the generating equipment is limited.

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# A Thermal Accelerating Relay

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IT is now common practice to start most medium and small-size alternating-current motors by applying the line voltage directly to the motor terminals. This method of starting has made popular an inexpensive type of remotely controlled line starter, usually inclosed in a relatively small, steel cabinet for wall mounting. This practice is limited by the application; for example, type of motor, nature of load, power supply, etc.

Where this method of direct-voltage starting cannot be used there is a demand for another starter of the same general, inexpensive type and class, to be used where one or more automatically controlled steps of acceleration are required before the motor can be connected directly to the line voltage. In order to meet this demand an inexpensive time-delay relay was designed and is described in this article.

Point or step starting of motors refers to the method of starting a motor gradually, in contrast to line starting, which gives a sudden start as the motor is initially connected directly to the line. Point starting means that there are connections in the motor circuit which are made only temporarily to start the motor and that other and permanent connections are made when the motor approaches its continuous running speed. There may be more than one set of points or temporary connections during starting, each set operating automatically in succession and at predetermined time intervals, and each set allowing the motor to attain a speed higher than the set before it.

Point starting of alternating-current motors may be required for many reasons. Some of them are:—

1—The inertia of the motor load may be such that the starting current must be limited during the starting period to prevent heating in the motor.

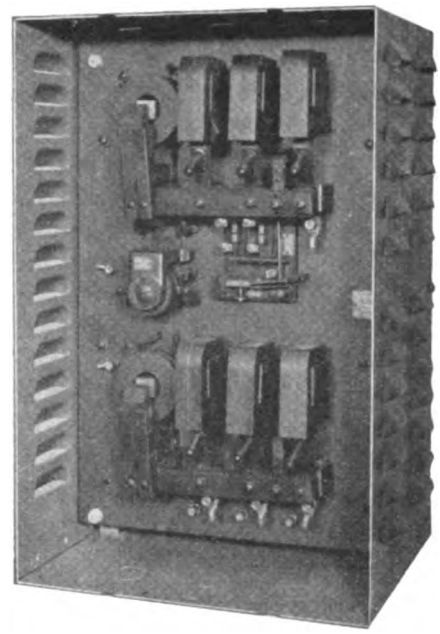
2—The power supplier may require that the starting current be limited and held below a given maximum value.

3—The motor or connected load may need protection from shock which would result from quick starting.

4—The motor may be of such size that line starting could not be used under any condition.

Point starting may be employed with both squirrel-cage and wound-rotor motors. If the starting current required by the load is low, a squirrel-cage motor may be used and started by connecting it in series with resistors across the line. The resistors are short-circuited at predetermined time intervals as the motor accelerates. If the starting torque is high, requiring excessive starting current, a wound-rotor motor must be used. Here, starting is performed by inserting resistors in the rotor circuit, which are short-circuited at the proper time intervals, as the motor speeds up.

Point or step starting may be accomplished by hand; or by some automatic means, such as a time-limit relay. Where time limit acceleration is employed, the relay must give the necessary time delay before operating. When the motor is started and the temporary starting circuit is established, the time relay also is started on its time cycle. When it comes to the end of its time cycle, the relay operates to change the temporary starting circuit to the permanent running circuit of the motor.



A TOTALLY ENCLOSED TWO POINT STARTER WITH THERMAL ACCELERATING RELAY FOR SQUIRREL-CAGE MOTORS

The accelerating relay is mounted just under the upper contactor. The starting resistors are mounted within the cabinet on the rear of the main panel.

The relay described here obtains this time interval by allowing heat to accumulate, which after a time causes the relay to act. The accumulated heat is stored in a strip of bimetal which responds in the form of mechanical work. Bimetal consists of two metals of different expansion characteristics, so that when its temperature is raised it will bend, due to the unequal expansion of the two metals.*

On the relay described a low temperature type of bimetal is used which is composed of brass and nickel-steel. This bimetal requires a relatively small amount of energy to operate it and is a good heat conductor. The small loading required makes it advantageous to use this type of bimetal. To obtain the necessary temperature, a current is passed directly through the bimetal itself. Fig. 1 (a) and (b) show the bimetal element at normal temperature. It is shaped with two lugs for the circuit connections, two long narrow sections and a thick center through which the current passes.

*See "Bimetal: The Temperature Sentinel" in THE ELECTRIC JOURNAL, for June 1928; also "The Theoretical Treatment", *Jour. of the Optical Society of American and Review of Scientific Instruments*, Vol. II, July—Dec. 1925.

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When current is flowing, the only places where appreciable temperature results are in the long narrow sections, since the current density is very much higher in these sections than elsewhere along the current path. For comparison, Fig. 1 (b) and (c) show the strip at normal and at operating temperatures respectively. The end opposite the lugs has an appreciable displacement which is used to trip the relay. The bending takes place only in the narrow sections as illustrated. The thick center between the two narrow sections has a much lower temperature than the narrow sections, hence the temperature gradient and the heat flow from these sections to the center is considerable for the short time the current is flowing. The heat flow is further increased because of the good heat conductivity of the metal. When the current is shut off, heat continues to flow from the narrow sections, allowing their temperature to drop rapidly. This is accompanied by a quick return of the bimetal to its normal position. Quick return or reset is desired so the relay will be ready for another cycle if desired by the operator. For this reason, and also to avoid overheating, it is essential that the power be interrupted when the relay trips.

As the length of the time interval required of the relay will vary with the application, it is necessary that the relay be made adjustable. This is accomplished by varying the current through the bimetal. The relation of current to time of trip is shown in Fig. 2, where it is easily seen that the time has an inverse relation to the current, if a given temperature must be reached in all cases; the greater the current, the shorter the time required to come up to temperature.

As seen from Fig. 2 the current to be supplied is considerable and therefore the problem of supplying this current at a low voltage is encountered. For alternating-current circuits the immediate answer is a transformer interposed between the line and the bimetal strip. This transformer, which must have a high-current, low-voltage secondary, is of the simplest

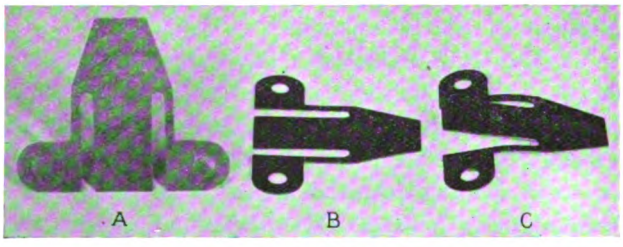


FIG. 1—THE BIMETAL RELAY ELEMENT
The element which carries a current is in its normal position in (a) and (b). At a higher temperature the bending takes place as may be seen in comparing (b) and (c).

type and was designed to have an intermittent rating for starting duty only. Transformers are usually built up of thin laminations of iron in order to break up the electric circuits through the iron which would exist if the core were solid; however, the transformer core shown in Fig. 3 (a), consists mainly of a cast-iron yoke. The use of cast iron is possible here since it is built for starting duty only, and the higher losses are not objectionable.

Through the yoke is placed a steel pin which completes the magnetic circuit. The pin is slotted to re-

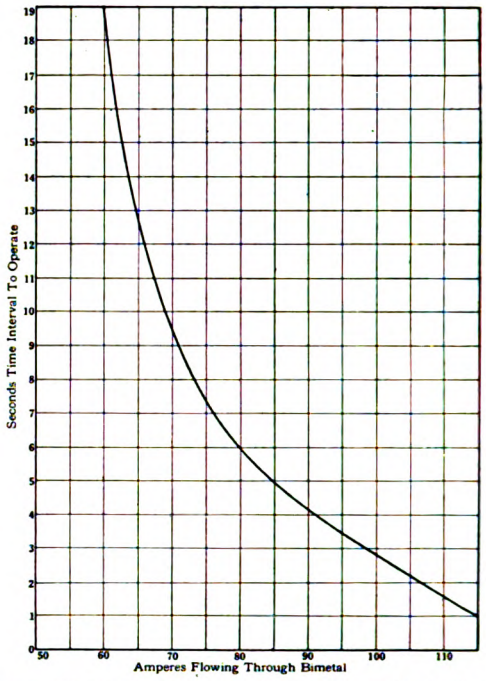


FIG. 2—THE INVERSE RELATION BETWEEN TIME AND CURRENT PASSED THROUGH THE BIMETAL
The displacement for a given temperature rise is the same for all currents.

duce its magnetic reluctance, and is held in place by a lock nut. When the pin is turned, an air-gap in the magnetic circuit may be varied. Fig. 3 (b) shows the complete secondary circuit composed of the bimetal, two connecting studs and the secondary winding. The latter consists of a few turns of copper strap wound on edge. It is shown with the ends connected to the studs which normally extend through the panel and are used as supports for the bimetal, as well as conductors of the bimetal current generated in the secondary coil. Fig. 3 (c), is the primary coil wound for

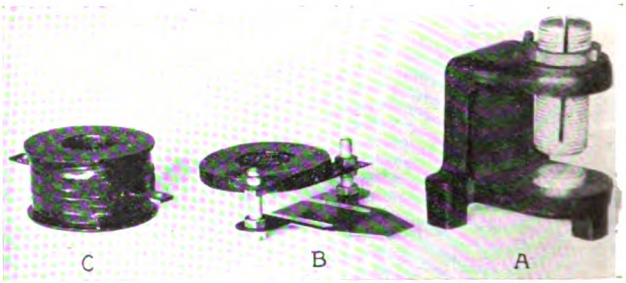


FIG. 3—TRANSFORMER FOR HEATING THE BIMETAL ELEMENT
(a) The transformer core is made of cast iron. The magnetic circuit is linked through the windings by a threaded steel pin. (b)—The secondary coil circuit is closed through the bimetal with studs. (c)—The primary coil is wound for line voltage.

line voltage. The primary and secondary coils are placed together in the yoke of the transformer and are linked in the magnetic circuit by the pin which passes through their centers.

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In order to change the current through the bimetal as required to vary the time of trip, the magnetic leakage between the primary and secondary coils and the exciting current are changed. This is done by varying the air-gap which, for a constant primary voltage, will change the secondary voltage and current. Thus the time of trip may be changed by turning the pin on the transformer. This adjustment will give a time change of a ratio of approximately 3 to 1. The time range is determined by the primary coil which, for example, may be wound for 1 to 3 seconds, or 4 to 12 seconds. For all voltages and frequencies the relay is the same except for the primary coil.

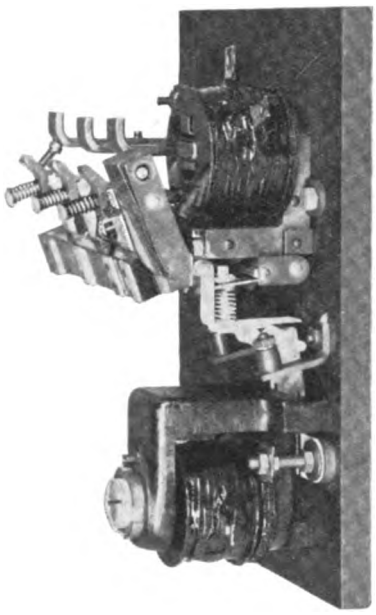

FIG. 4—THE RELAY MOUNTED UNDER A CONTACTOR WHICH IS IN THE "OFF" POSITION. THE TWO UNITS ARE LINKED THROUGH A LATCH WHICH CARRIES A MOVING CONTACT

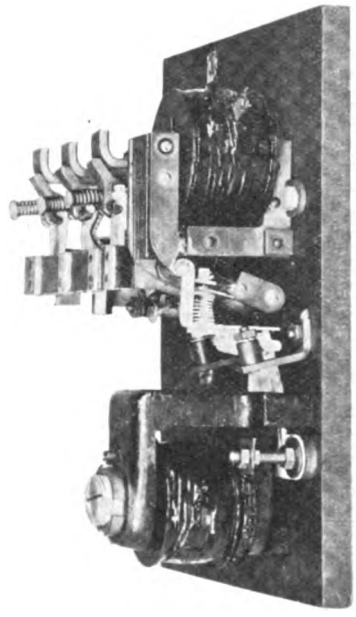

FIG. 5—WHEN THE CONTACTOR AND RELAY ARE ENERGIZED, THE CONTACTOR CLOSES AND THE BIMETAL BEGINS MOVING TOWARD THE END OF THE LATCH

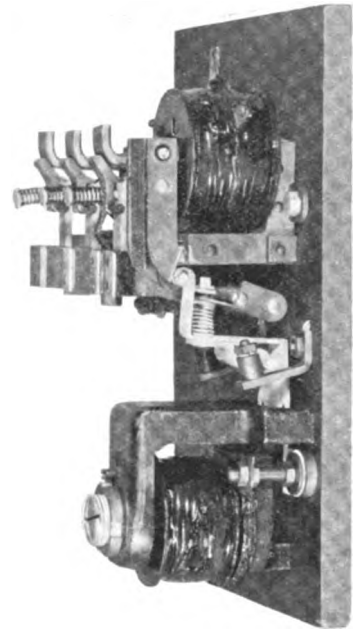

FIG. 6—THE BIMETAL HAS CLEARED THE LATCH, WHICH IS ALLOWED TO CONTINUE ITS MOVEMENT UNTIL THE CROSS BAR BRIDGES THE CONTACTS

For the relay to open or close electrical contacts with a quick make or break, it must trip a latch which carries the contacts. Some means must also be provided to reset the latch for a second start. To get an automatic reset the relay is mounted in connection with a contactor, so that the latch is reset when the contactor opens. Fig. 4 shows the relay as normally mounted under a contactor. Here the contactor is in the open position. The transformer is shown mounted on its three legs, two of them astride the bimetal element, which is parallel to and a short distance from the panel. The contactor has a section of its armature cut away to expose the relay latch which is pivoted around the contactor center pin. The latch carries an insulated cross bar mounted in such a way that it will bridge two contacts when it touches them. A spring tends to rotate the latch clockwise.

In Fig. 5, the contactor is closed, as is the case when its coil is energized. The latch is allowed to rotate about the center pin until obstructed from moving farther by the bimetal strip, which prevents it from closing its contacts. Simultaneous with the energizing of the contactor coil, the relay primary is also energized, and the end of the bimetal begins to bend toward the panel. Fig. 6 shows the condition when the bimetal has bent far enough to allow the latch to trip, and the cross bar to bridge the contacts by further rotation about the center pin under pressure from the spring. These contacts serve to energize another contactor which represents the second point of acceleration. For a new start it is necessary for the contactor to open and reset the relay as in Fig. 4.

The usual circuit for squirrel-cage motors is shown in Fig. 7. The relay is mounted below and reset by the main line contactor 5. The start button energizes main contacts 5, which, through an interlock, establishes a holding circuit. The relay primary circuit

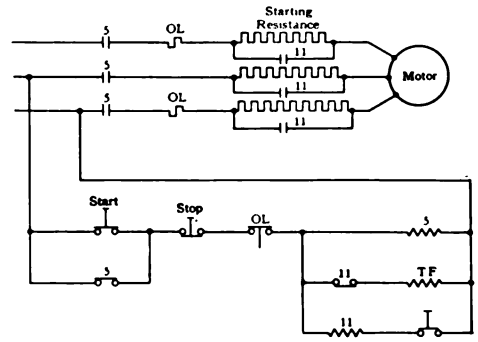


FIG. 7—SCHEMATIC DIAGRAM SHOWING THE USUAL CONNECTIONS WHEN THE RELAY IS USED ON A SQUIRREL-CAGE MOTOR STARTER

More starting steps could be used if desired by adding more relay and contactor units.

TF is also energized through an interlock on contactor 11. The motor accelerates at reduced voltage until the relay trips, closing the circuit of coil 11. This closes the main contacts 11, and interlock 11 opens the relay coil. Both contactors remain closed while the motor is running.

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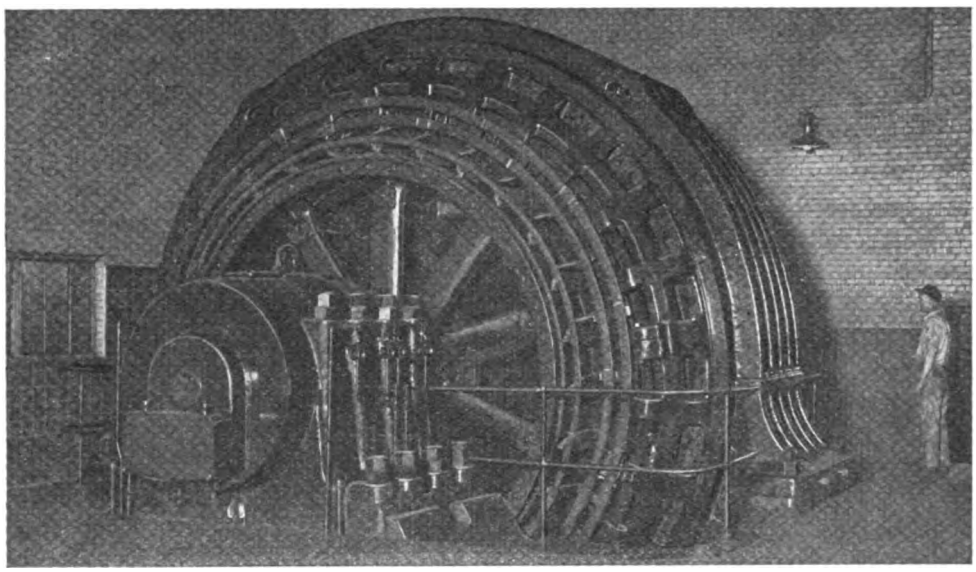

**The Largest Single-Unit Direct-Current Motor ever built. An 8000 hp, 700 volt 40/80 r.p.m. reversing mill motor. This motor is capable of exerting a maximum momentary torque of three million pounds feet at full-field speed. It was built for the Homestead Steel Works of the Carnegie Steel Company. The weight of the motor complete is 646 735 pounds.**

# Structural Features of an 8000 H-P. Reversing Direct-Current Mill Motor

**H. E. STOKES and C. P. CROCO**
Power Engineering Dept.,
Westinghouse Electric & Mfg. Co.

A FEW pounds pressure exerted by the operator on the foot master switch sets in motion the rolls of the largest blooming mill in the world and a glowing 15 ton ingot of steel is drawn and squeezed down between the rolls with a force of two and one-half million pounds feet. The invisible giant actuating the rolls is an 8000 hp direct-current motor —the largest single-armature direct-current reversing mill motor yet built. This motor has a continuous rating of 8000 hp, 700 volts, 40 to 80 r.p.m. by field control.

Reliability has been the keynote in the construction throughout. The experience obtained in the building and from the operation of over fifty motor-driven reversing mills has been incorporated in the design. The following paragraphs describe some of the special features which contribute to successful operation under what is probably the heaviest kind of duty in the wide field of service performed by the electric motor.

The magnet frame is of cast steel heavily ribbed on the outer diameter for stiffness. It is split horizontally for convenience in manufacturing and erection. The holding down bolts in the lower portion are carried through the bedplate into the concrete foundation. The magnetic section is made ample, so there is no strangulation of magnetic flux under conditions of peak loads, when the normal frame flux is heavily augmented by the commutating-pole flux.

The main poles are of laminated steel riveted together and heavily bolted to the magnet frame. The pole face is slotted axially to carry the compensating or pole face windings. The commutating poles are of laminated steel, riveted together and tapering out from the armature toward the magnet frame; near the magnet frame they are flared out to a wide seat to minimize the stresses in the holding on bolts due to the reversing nature of the pull of the commutating poles to the main pole. The tip near the armature is shaped to obtain the correct flux densities for neutralizing the fluxes in the armature coils undergoing commutation. The laminated structure serves the double purpose of minimizing pole-face losses and also of securing a rapid change of commutating-pole flux in magnitude and direction to synchronize with similar changes in the load current.

The main pole coils consist of a shunt and series coil. The shunt winding furnishes excitation required for any speed from normal of 40 r.p.m. to the maximum of 80 r.p.m. The series coils give additional flux and torque to the motor, depending on the load conditions. Inasmuch as the current in the series coils varies in direction with the rotation of the motor, the current has to be reversed with the rotation, and if the coils carried the load current, the current to be handled in reversing would be unwieldly. The load current is therefore passed around the field pole of a variable potential exciter, the armature of which is connected to the series coils. The arrangement results in series current of such a magnitude as to be easily handled in reversal.

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Both shunt and series coils are of bar strap coil wound on edge and insulated between turns with asbestos. Air ducts are arranged to permit of free circulation of air between coils.

The compensating or pole-face windings are of heavy strap pushed through the pole face slots, and are connected at the ends by bare copper straps bolted and soldered to the pole face bars. The current density at the joints is kept very low. The projecting

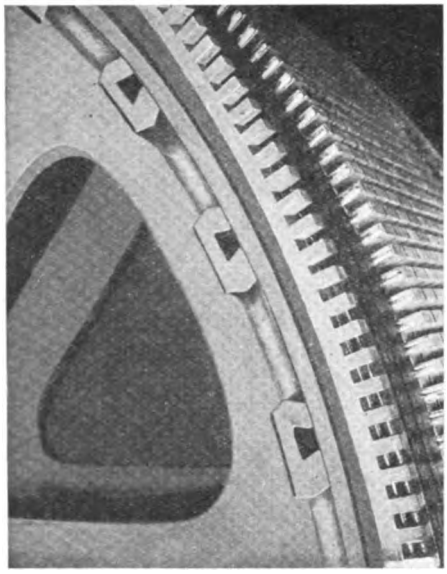

FIG. 1—SLOTTED COIL SUPPORT

ends of the pole face straps are heavily insulated for a considerable distance from the frame to prevent creepage.

The commutating pole coils are of bare flat rolled strap formed to be parallel to the taper of the commutating pole body to utilize to the best advantage the space available. The coils are positioned as close as possible to the armature to shield the commutating-pole flux from the distorting influence of the main pole and armature. Insulated through-bolts secure the commutating pole coils to the pole body. The coils are insulated from the poles by an insulating trough.

The armature is designed with as small diameter and as long length as is consistent with good commutating performance for the purpose of reducing to a minimum the flywheel effect. The long armature also is effective in giving high efficiency; the total losses of the direct-current generators and motor on this installation are not over eleven percent of the input at normal full load.

The armature spider consists of a single steel casting with arms heavily ribbed axially and transversely, and the periphery consists of four rings on which are cast the ribs in which the dovetails are machined. The spider is designed for great strength, but also allows of free circulation of air through the punchings for the purpose of cooling. The armature coils are mica insulated throughout for 1500 volts and at both ends are supported in slotted coil supports to prevent them lagging behind the portion carried in the core during periods of acceleration and deceleration. This arrangement permits the end coils being opened up to free circulation of air between coils, allowing a high continuous rating of the motor. The same precautions taken to prevent relative movement of the armature end coils are also taken in regard to the armature cross connections and these are carried at the rear end of the armature on the rear end of the slotted coil support. These are clamped endways against a radial rib of the coil support extending inwards in the direction of the shaft and are also clamped in a radial direction against a ringed projection of the rear armature end coil support. The cross connections are riveted and soldered to the armature coils. The armature end coils are held down by sectional bands located over the slotted coil support portion of the coil.

The commutator is carried on a separate spider and both armature and commutator spiders are keyed to and pressed on the shaft. To prevent relative movement of the two, the commutator spider arms are bolted to extensions of the armature spider near the periphery of the commutator spider. The armature and commutator spider are also bolted together at coupling like extensions of both at the hubs.

The construction of the commutator, armature coil supports and cross connections described above, has been employed in a large number of blooming mill and reversing mill drives and there is no single instance of failure.

The mill end pedestal is of cast steel and the commutator end pedestal of cast iron. In case of breakage

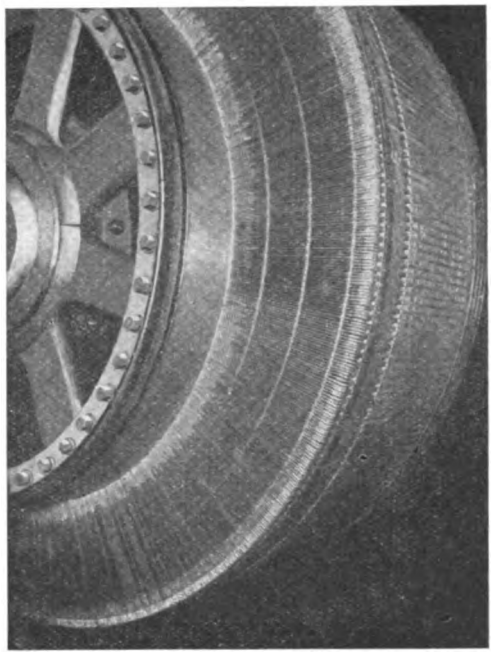

FIG. 2—COMMUTATOR CONSTRUCTION

of a mill spindle, there is a severe thrust on the mill end pedestal and this is especially designed to take care of such an emergency. This pedestal is of short height and on the outer or mill end is provided with a thrust bearing. The end thrust from the mill is transmitted to the thrust bearing on the mill end motor pedestal

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through the roll drive shaft and coupling. On the end of the motor half coupling next to the thrust bearing a race is machined to ride on the surface of the thrust bearing during the impact from the mill. Under

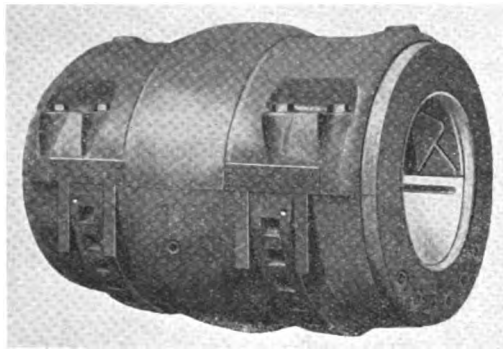

FIG. 3—SELF ALIGNING BEARING

normal operating conditions there is a small clearance between the race and the surface of the thrust bearing.

The thrust bearing face is babbitted and is furnished with pockets for oil waste lubrication. A guard is provided around the thrust bearing for the double purpose of oil drainage and for the exclusion of foreign matter from the bearing.

The mill end pedestal is cross keyed to the bedplate and the holding down bolts for both pedestal and pedestal cap pass through the bedplate and are anchored into the foundation. As a further precaution, the cap bolts are threaded below the pedestal cap split and a nut is tightened down on the pedestal lower half before the cap is put on and another nut is used to secure the cap in place.

Both front and rear bearings are of the self-aligning type, provided with ring and gravity feed lubrication. The mill end bearing is 32 inches in diameter. The bearings are cooled by circulating water through brass tubes cast into the bearing babbitt.

The bedplate is cast iron, split in halves for convenience in handling and shipment. The depth of the bedplate is much greater than is usual and it is heavily reinforced with ribs and provided with holes for grouting in to obtain maximum resistance to end thrust from the mill and to withstand the pounding shocks inherent with this type of mill.

The front end of the shaft is furnished with a gear and pinions for an overspeed device and a speed indicating magneto which operates voltmeters calibrated in revolutions per minute mounted in the operator's pulpit and on the switchboard. The pinions and gear are enclosed by a suitable cover.

Owing to the comparatively low average peripheral speed of operation of the armature, the natural circulation of air through the windings is inadequate, and forced ventilation is employed to obtain the desired rating for the material used in the electrical and magnetic parts. A cast iron shroud, split horizontally and also vertically in the lower half is carried from the rear end of the magnet frame to a point near the armature coils. This is used to prevent the ventilating air applied to the rear end of the motor from flowing in unnecessary volume through the field windings. A second end bell connected to a duct below the bedplate, and to the rear end of the field shroud, supplies the ventilating air in the correct proportions to the armature and field system. A sheet metal shroud is provided on the front end of the armature spider to prevent the air from blowing through the armature spider and out at the front end. The air entering the rear of the armature passes through the core ventilat-

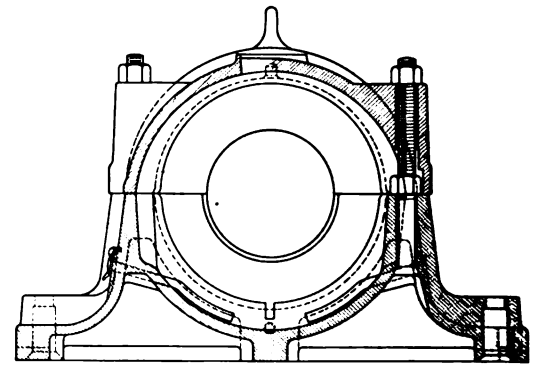

FIG. 4—SECTION THROUGH PEDESTAL

ing ducts, or through the clearance between the armature end coils, and joins that passing between the field coils and thence out into the motor room. The ventilating air is taken from the outside and thoroughly washed and dried before passing through the blowers to the motor duct.

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## New Subway Cars for Philadelphia

Philadelphia is soon to put into operation in its new Broad Street subway 150 new cars of the latest design for rapid transit service. Each car is 67.5 feet long and seats 75 passengers. All cars are motor cars, two 200 hp motors being used on each. The free running speed is 47 miles per hour on level tangent track at 600 volts.

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# The Step Induction Regulator

## For Transformer Voltage Control

R. M. FIELD
Transformer Engineering Dept.,
Westinghouse Electric & Mfg. Co.

EQUIPMENT for controlling the voltage of power transformers under load is coming into common use. The taps of the transformer are usually changed by means of circuit-breaker or switching equipment which permits the voltage of the transformer to be varied in steps of from 2 to 2.5 percent.[1] When the voltage of a large power transformer is to be varied in a number of very small steps with the step-type tap changer, a large number of circuit breakers or switches are required. The step induction regulator, however, alleviates this difficulty, as with it a relatively small number of switches are required. Moreover, this equipment is especially adaptable to small power transformers where a large range in voltage is required, and to transformers where it is desired to vary the voltage in a smooth curve. The step induction regulator method of voltage control switches an induction regulator across the taps of the transformers and gives smooth-curve voltage control with an infinite number of operating positions.

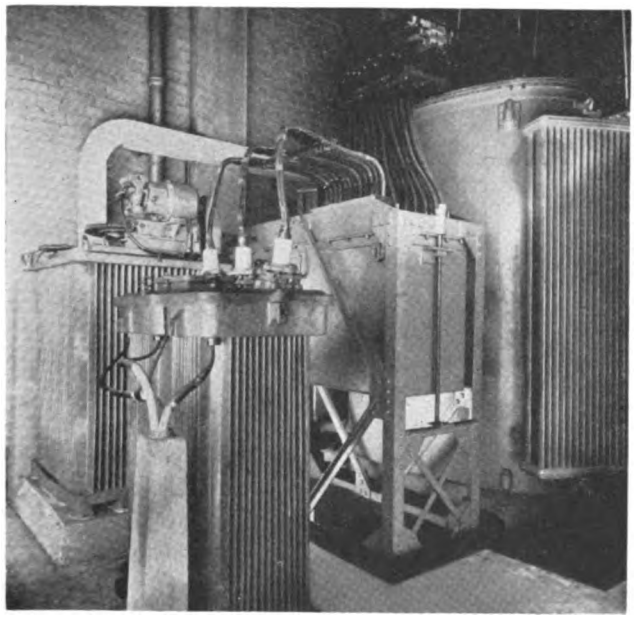

FIG. 1—STEP INDUCTION REGULATOR FOR 50 PERCENT VOLTAGE CONTROL OF A 2500 KV-A, THREE-PHASE TRANSFORMER[2]

The step induction regulator was first used with furnace transformers where it was necessary to control the voltage over a large range. While the kv-a of these transformers was usually small as compared to a modern power transformer, the range in voltage variation was usually of the order of 50 percent, and it was more economical to supply switching equipment to connect a small induction regulator across the taps of a transformer than to use an induction regulator of relatively large power capacity. The step induction regulator was later adapted to power transformers for voltage control of synchronous converters and transmission lines. Typical step induction regulators are shown in Figs. 1, 2 and 3.

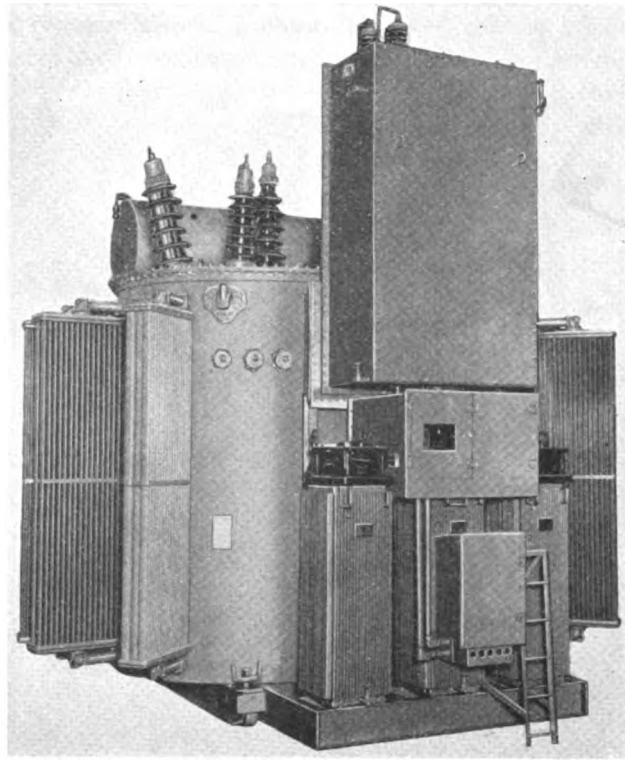

FIG. 2—A 6850 KV-A, THREE-PHASE TRANSFORMER WITH STEP INDUCTION REGULATOR MOUNTED INTEGRAL WITH THE TRANSFORMER

A schematic diagram of a transformer winding with its taps connected through the switching equipment to the series transformer and induction regulator is shown in Fig. 4. The selector switches connect, as described later, the series transformer and induction regulator along the transformer taps in the sequence shown. The transfer switches are used to change the windings of the double-secondary insulating transformer when there is no difference of potential between the selector switch contacts.

Rotation of the induction regulator rotor through 180 degrees changes the voltage in its stator from a maximum in one direction to a maximum in the other direction as shown in Fig. 5. By operating the regulator and selector and transfer switches in the proper sequence, the regulator is connected so its voltage adds to or subtracts from a transformer tap, thus varying the voltage from tap to tap.

[1] "Transformer Tap Changing Under Load"—L. H. Hill, *A. I. E. E.*, Nov. 1927.

[2] "Step-Induction Regulator-Controlled Synchronous Converters"—M. F. Packard, *Elec. World*, Oct. 9, 1926.

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With the equipment set on the zero point, switches 1 and *A* are closed, and the regulator is in the zero voltage position. If the winding which is provided with taps is considered as the secondary winding of

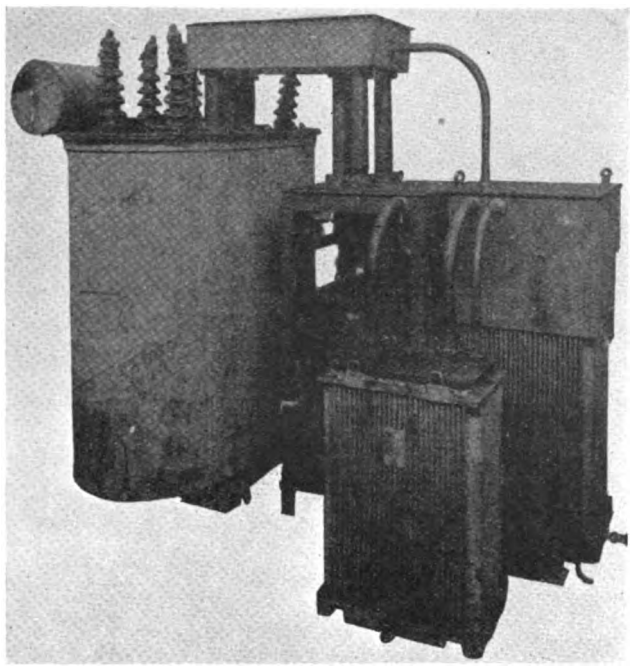

FIG. 3—STEP INDUCTION REGULATOR FOR 28 PERCENT VOLTAGE CONTROL OF A 15 000 KV-A, THREE-PHASE TRANSFORMER[3]

the transformer, some minimum voltage will be induced in it. To increase the secondary voltage, the induction regulator is rotated and an increasing voltage is added to tap 1 through the winding *M* of the series transformer. When the maximum boost voltage of the regulator is added to tap 1 through winding *M*, the maximum voltage in the opposite direction will be induced in the winding *N* of the series transformer. As the sum of these two voltages equals the voltage between taps, selector switch 2 and transfer switch *B* may then be closed to subtract the maximum voltage of the regulator from tap 2. Since the voltage induced in windings *M* and *N* are approximately equal there will be no change in line voltage if winding *M* is disconnected from tap 1 by the opening of switches *A*

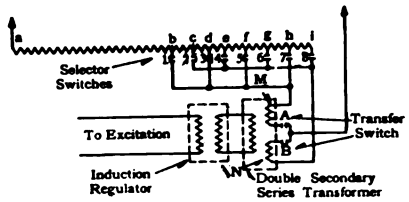


FIG. 4—SCHEMATIC DIAGRAM OF TRANSFORMER AND STEP INDUCTION REGULATOR WINDINGS

and 1. The voltage of the transformer winding is then increased by rotating the regulator to decrease the voltage in winding *N*, which is subtracted from tap 2. Further increases in voltage are obtained by continued rotation, the switches operating in the sequence shown in Fig. 5.

[3] "The Tacoma-Seattle Power Exchange Line"—R. E. Towne, THE ELECTRIC JOURNAL, June, 1923.

The three single-phase series transformers are mounted on the end frames of the main transformers and, like the main transformer, are of the shell form of construction. The taps from the transformer and the series transformer leads are brought to a terminal

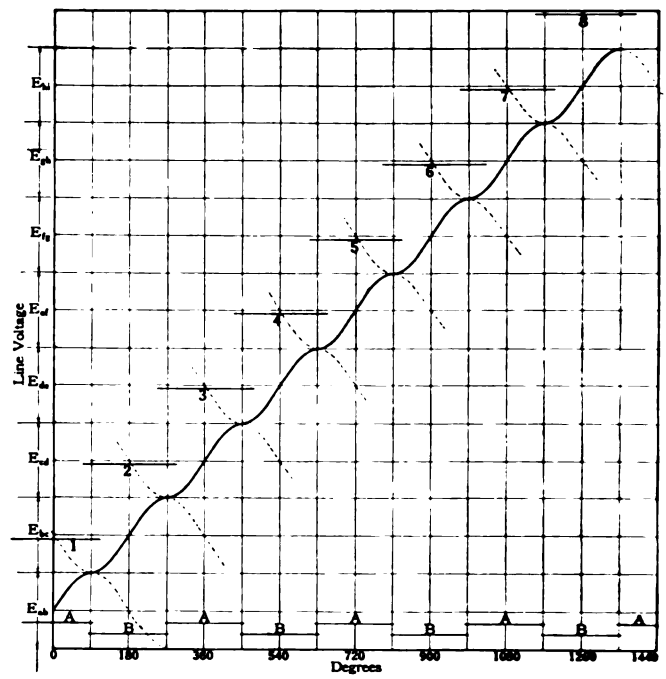


FIG. 5—SEQUENCE DIAGRAM OF REGULATOR CONTACTS

board which forms an integral unit with the transformer.

The contactor switching equipment is shown in Fig. 7. The corresponding switches of the three phases are mounted one above the other on a micarta plate, and are operated simultaneously. The stationary contact is rigidly fastened to a stud which is bolted to the micarta plate, while the moving contact is pivoted on a second stud. A heavy spring holds the two contacts together when in the closed position. A shunt

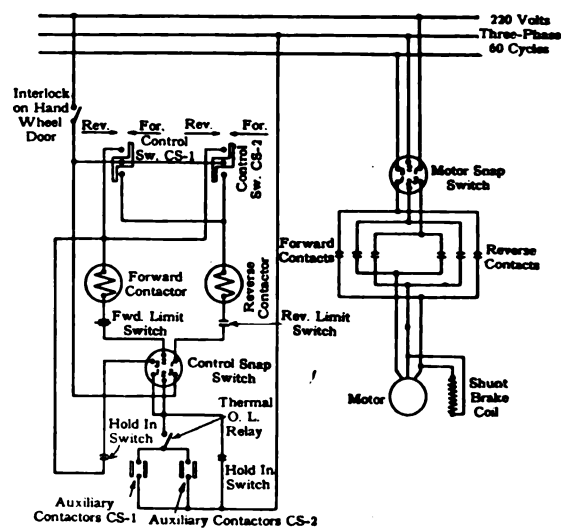


FIG. 6—SCHEMATIC DIAGRAM OF CONTROL EQUIPMENT

carries the current from the contact to the stud, thus preventing annealing of the spring by current passing through it. The taps from the transformer are connected to the switches through the studs at the rear of

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the insulating plate.

Insulated shafts connect the moving contacts of the switches of each phase to the cam operating mechanism. Rotation of the cam forces the insulated shaft upwards to close the switch, the switch remaining closed as long as the lobe of the cam is in contact with the roller of the operating shaft. With continued rotation of the cam, the roller and operating shaft drop down, opening the switch. An opening lobe is also provided which insures positive opening of the switch.

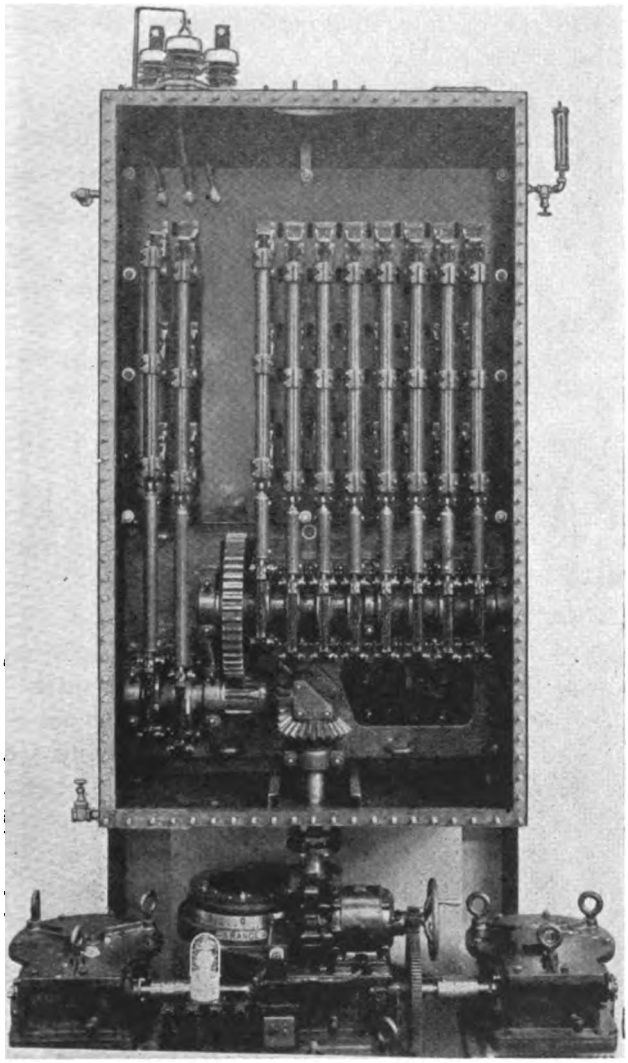

FIG. 7—CONTACTOR SWITCHES OF STEP INDUCTION REGULATOR

The sequence of operations of the selector and transfer switches is such that the transfer switches open before and close after the selector switches, and hence only the transfer switches open and close the circuit. Since the transfer switches interchange the windings of the double-secondary insulating transformer when there is no difference of potential between the contacts, arcing and therefore maintenance are reduced to a minimum.

The operating motor is placed midway between the switch compartment and the induction regulators, as shown in Fig. 8. Each induction regulator is provided with a worm and gear, the gear being directly connected with a horizontal drive shaft, to which the motor is connected through a spur reduction gear. The center induction regulator is provided with a shaft extension and a flanged coupling to which the vertical shaft of the contactor cam operating mechanism is connected. The motor operating mechanism is completely enclosed, as shown in Fig. 2, the enclosing compartment being provided with doors for inspection and for hand operation.

The equipment is normally motor operated and remotely controlled from a control switch located at the switchboard. Fig. 6 gives a schematic diagram of the control equipment. This control equipment is similar to that used on step-type tap changers.[4]

The control switch has two operating positions, with a central or *Off* position. Turning the switch to an operating position closes a magnetic contactor which is mounted in a weatherproof cabinet on the

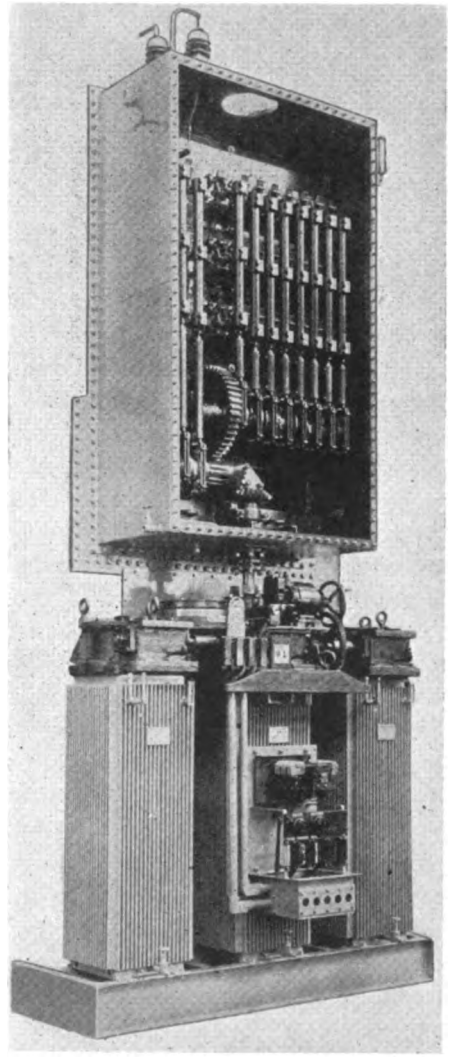

FIG. 8—COMPLETE STEP INDUCTION REGULATOR WITH HOUSING REMOVED

center induction regulator, as shown in Fig. 8. The closing of the contactor completes the supply circuit to the operating motor and the mechanism moves in

[4] "Control and Relay Equipment for Motor-Operated Transformer Tap Changer"—W. R. Farley, THE ELECTRIC JOURNAL, Sept., 1927.

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a forward direction, from zero to 100, to connect in taps of the transformer winding. The control switch is manually held in the operating position until the desired voltage is reached. The return of the switch to the *Off* position opens the circuit of the contactor, which in turn opens the supply circuit to the motor and operates the magnetic brake.

The equipment is provided with the transmitter element of a position indicator. This element is electrically connected to a receiver element mounted at the switchboard, to indicate the position of the equipment. The dial of the position indicator is graduated from zero to 100, corresponding to the scale of the mechanical position indicator shown in Fig. 7, mounted on the equipment.

In addition to the position indicator, two white and two red incandescent lights are provided for mounting on the switchboard. The two red lamps are used to indicate the limit of travel in the *Forward* and *Reverse* directions. One of the white lights is connected to a source of power through a contact on the door of the operating mechanism. The opening of the door closes this contact and also opens a contact which disconnects the control circuit. The white light indicates to the operator that he no longer has remote control of the equipment.

The second white lamp is wired in the control circuit to give the operator a visual signal, in addition to that of the position indicator, that the equipment is in operation and that the transformer voltage is being varied.

In addition to remote control initiated by an operator, the step induction regulator may also be arranged for automatic operation to give smooth voltage control in response to voltage fluctuations of the system.

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# Fluid Governors for Prime Movers

## IV—Operating Mechanisms (Cont'd)

HENRY F. SCHMIDT

A GOVERNOR mechanism similar in principle to that of Fig. 28 has been proposed by Mason, and is shown in Fig. 29. The mechanism consists of the operating piston *A*, relay valve *B*, differential nut *C*, and ports *E* and *F*, whereas in Fig. 28, the differential motion was obtained by means of an internally and externally threaded sleeve. In Fig. 29, the sleeve *C* is threaded externally to engage with studs *D*, and the internal thread of Fig. 28, is replaced by helical ports *E* and *F* in the operating piston trunk and relay valve sleeve *B;* the helical ports having a smaller pitch than the threads of the sleeve *C*. The relay valve *B* is kept from turning by a square end on the piston rod projecting through the cover. If the operating piston *A* and its trunk move upward or downward, a rotary motion is imparted to the operating piston rod, causing the ports *E* and *F* to communicate with each other, admitting oil under the piston *A* and forcing the piston upward until the rotary motion of the piston cuts off communication between the ports.

The speed change is accomplished by rotating the sleeve *C*, which changes the position of the piston *A* with respect to the relay valve *B*, causing the ports to register at a higher or lower oil pressure.

Another principle for obtaining the differential motion desired is shown in Fig. 30, in which no levers, screws, etc., are employed. The general idea on which this mechanism is based is that the motion of any intermediate point of a spring when the spring is compressed or elongated is proportional to its distance from the end. In this case, the spring giving the differential motion has two parts *A* and *B*, with a distance piece *C*, having a feather key drive from a worm wheel *D* which is used for obtaining change of speed. The governor spring *S* is attached at its upper end to a shackle nut *E* having an extended threaded portion which engages with threads in the distance piece *C*. The stem *E* is kept from rotating by a feather key in the guide *F* carried by the operating piston trunk, the lower operating piston trunk being keyed to the housing at *G*. The relay valve sleeve is the same as in the other mechanism shown. When the operating piston moves downward, part of the compression in the springs *A* and *B* is relieved, causing the spring to elongate. The spring *A* being stiffer than the spring *B*, will move less for a given change of load than the spring *B*, and consequently the distance piece *C* will not move down quite as far as the operating piston, thus stretching the spring *S*. When the operation is reversed, the spring *A* compresses less than the spring *B* causing the sleeve *C* to move upward less than the operating piston, thus elongating the spring *S*, and increasing the load.

When the speed changer worm wheel *D* is rotated, the shackle nut *E* is screwed up or down in the nut in the distance piece *C*. This increases or decreases the tension in the spring, *S* causing a change of speed. Ball bearings are provided as abutments for the springs *A* and *B*, to prevent subjecting them to torsion and to make the operation of the speed changer easier.

Probably the simplest differential spring motion is shown in Fig. 31. The principal parts of this arrangement are the same as those previously described, except that here the differential motion of the spring is obtained by means of the lever *A*, one end of which rests on the fulcrum *F*, supported by the housing, *H*.

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and the other end on the operating piston trunk $T$, the spring being attached to a threaded member screwed in a trunion sleeve, $S$, carried by the lever $A$. Motion up or down of the operating piston causes a slight extension and contraction of the governor spring, thus changing the load an amount equal to the change of pressure due to the speed variation required times the area of the relay valve sleeves. The speed variation of this mechanism can be changed by moving the fulcrum point $F$ closer to or farther away from the trunion. By making the fulcrum a cam in place of a knife edge, the variable motion of Fig. 19 can be obtained, and the necessity for ported valve sleeves obviated.

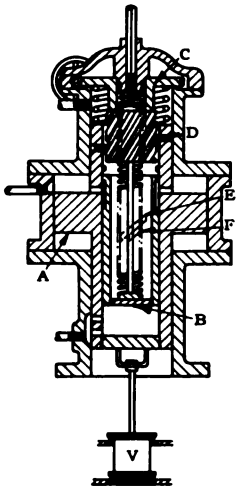


FIG. 29—THE MASON GOVERNING MECHANISM

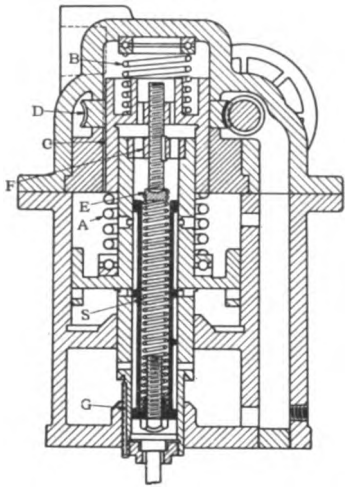


FIG. 30—A MECHANISM WHICH OBTAINS A DIFFERENTIAL MOTION WITHOUT THE USE OF LEVERS

By means of the speed changer wheel $W$, the threaded member to which the governor spring is attached can be rotated in the threaded trunion sleeve,

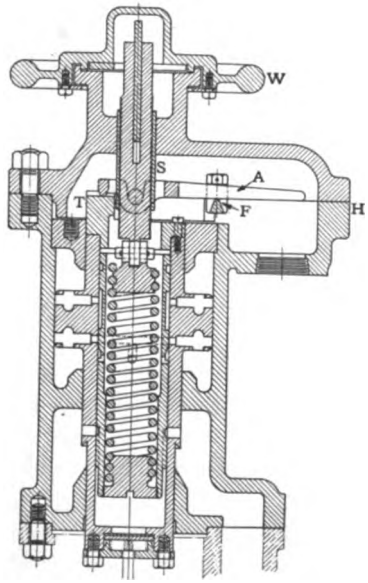


FIG. 31—A SIMPLE MEANS OF SECURING DIFFERENTIAL SPRING MOTION

which is kept from rotating by the trunion. The great advantage of this arrangement is its simplicity and the ease with which it can be assembled and taken apart.

In any of the mechanisms described, the speed can be changed from practically zero to the maximum fixed by the strength of the spring, while the turbine is in operation, by means of the speed changer. However, if the governor springs are so designed that they have a normal speed variation of two or three percent at full speed, the speed variation will be very large when running at reduced speed. The difficulty can be very easily overcome in the type of mechanism shown in Fig. 31, by either of the mechanisms shown in Fig. 32 and 33.

As previously pointed out, the speed variation, or effective scale of the spring, can be varied by moving the fulcrum point $F$ closer to or farther away from the spring. In order to maintain substantially the same speed variation at low speed as at high speed, the operating mechanism of Fig. 32 is equipped with an auxiliary cylinder and piston. The piston, which is resisted by a spring, is attached to the fulcrum $F$. The stiffest spring is required at the highest speed, that is, when the fulcrum is at its innermost position, and the weakest scale is required at low speed when the fulcrum is at its outermost position. Governor oil pressure is admitted behind the auxiliary scale-changer piston, so that as the tension of the main governor spring is increased, increasing the speed and the governor oil pressure, the fulcrum is moved in closer to the center, and as the tension of the governor spring is decreased for decrease of speed, the spring forces the piston out and moves the fulcrum farther away from the center.

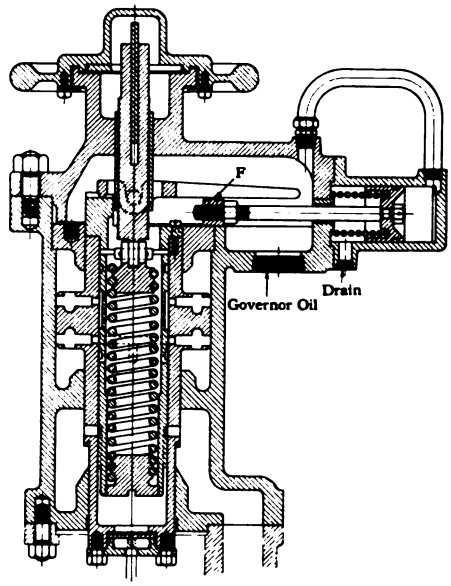


FIG. 32—GOVERNING MECHANISM IN WHICH ACCURATE SPEED CONTROL IS OBTAINED BY AN AUXILIARY CYLINDER AND PISTON

The same effect as is obtained by means of the piston in Fig. 32, is obtained in Fig. 33 by means of a screw driven by gearing from the speed-changer motor, which is also geared to the governor spring tension adjusting nut. The screw driven by the speed changer engages a threaded portion of the fulcrum and is so arranged that as the tension of the governor spring is increased, the fulcrum is moved nearer to the center, and vice versa.

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Relay arrangements employing a different principle of operation are shown in Figs. 35 and 36. Here, in place of the load spring of Fig. 23, oil pressure is employed on the opposite side of the relay valve sleeve. In Fig. 35, the spring $S$ replaces the scale spring of Fig. 23, and the load spring is replaced by the relief valve $V$, which is so adjusted as to maintain a pressure above the relay valve sleeve such that the total downward force is equal to that which would be taken by the load spring in the arrangement of Fig. 23. The chamber above the relay valve sleeve is closed except for the valve $V$, so that leakage past the relay valve sleeve builds up pressure until it is relieved and maintained constant by the relief valve. The change of speed is easily accomplished in this arrangement by simply changing the tension of the relief spring so as to vary the load on top of the relay valve sleeve. The pressure maintained in this closed chamber is always sufficiently less than that supplied by the impeller that there will always be sufficient force to operate the relay.

Figure 36 is similar to Fig. 35, except that here a separate piston is provided for carrying the load instead of using the upper end of the relay valve sleeve. This arrangement is not as desirable, as the ideal condition of having the relay valve free and with no other function than to move itself is lost because of the friction of the additional piston and valve stem. This arrangement, however, permits the impeller suction pressure to be imposed on the upper end of the relay valve sleeve, thus eliminating the

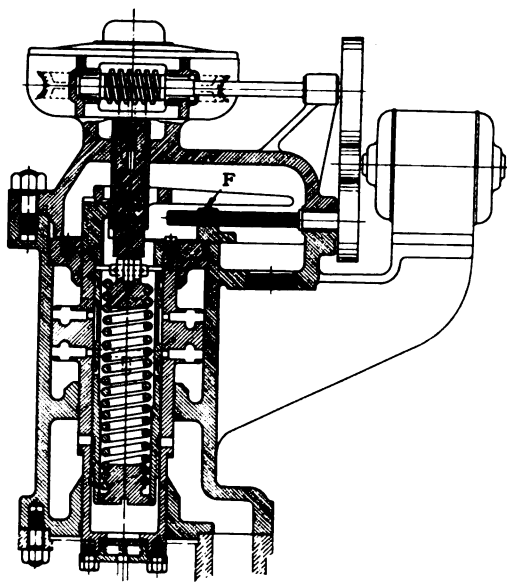


FIG. 33—THE GOVERNING EFFECT SECURED IN FIG. 32 AS OBTAINED BY GEARING

effect of variations in the suction pressure. It will be obvious, however, that since the relief valve maintains a constant difference of pressure between its high and low pressure sides, the variations of pressure in the impeller inlet chamber can be imparted to the top of the relay plunger, Fig. 35, by connecting the discharge of the relief valve to the impeller inlet chamber and this is done in some designs.

Various schemes have been proposed for shutting down the turbine in case of failure of the governor oil pressure; the earliest of these being that of Ehrhart previously mentioned. Practically all the schemes proposed have involved some mechanism which shut the steam valve when the pressure under the oil piston fell below a certain predetermined

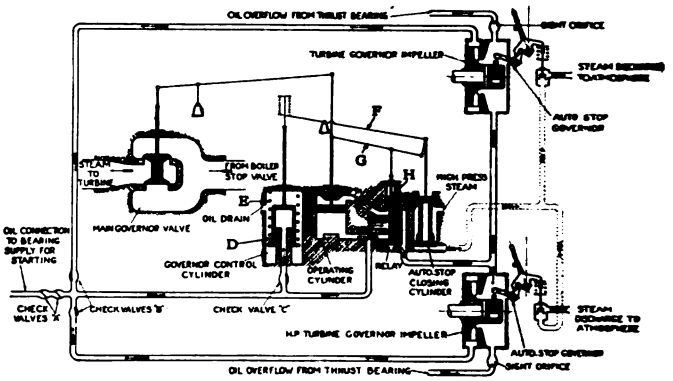


FIG. 34—AN EARLY TYPE OF OIL GOVERNOR RELAY MECHANISM

point. Unfortunately, none of these devices is actually of much value in service, for the reason that when the oil supply fails gradually, as for instance by a gradual loss of oil from the reservoir, the discharge pressure from the governor impeller does not immediately start to fall. As long as almost sufficient oil is delivered to the impeller inlet, the turbine, under the action of the governor, will tend to keep the governor discharge pressure constant with an increase of speed. This is due to the fact that the centrifugal force in the impeller holds the oil within it in an annular ring which becomes narrower and narrower as the oil supply is diminished, the speed increasing gradually, so that the centrifugal force on the remaining annulus of oil in the impeller is sufficient to equal the governing pressure. Thus it is entirely possible, as the writer has found by experiment, for the turbine to increase 50 or even 75 percent in speed and continue governing at this higher speed for quite a long while, when the oil supply to the impeller has been intentionally decreased.

Since the pressure at the inlet to the impeller would decrease to zero, or even fall below atmospheric pressure under some conditions when the oil supply is not ample, Hodgkinson has suggested the low pressure stop device shown in Fig. 37, in which the failure or decrease of the oil supply to the governor impeller causes the machine to be shut down. The governor itself, shown in Fig. 37, is substantially the same as that shown in Fig. 25, with the addition of the low-pressure tripping device. This consists of a valve $V$, to which is attached the valve stem $A$. The pressure of the oil supply to the impeller acts on the under side of the valve $V$, and compresses it against the spring $B$, holding the valve stem $A$ in the position shown. The valve and spring are so designed that when the pressure on the under face falls below

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three pounds, it goes through its whole travel, similar to an automatic stop plunger, bringing the ports *C* and *D* into communication, thus relieving the pressure above the operating piston and permitting a

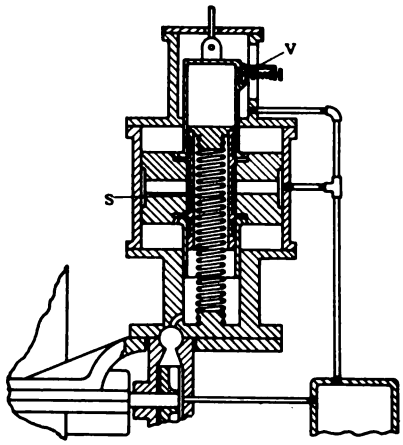


FIG. 35—A RELAY ARRANGEMENT IN WHICH OIL PRESSURE IS USED IN PLACE OF A LOAD SPRING

powerful spring upon the steam valve to draw the operating piston upward to close the turbine admission valve.

One of the earliest oil governor relay mechanisms employed is shown in Fig. 34, which has been used on a number of marine installations. Here the governing piston, operating piston and relay valve are separate.

Oil from the impeller is delivered through the governing piston to the governing cylinder *D*, which in this case is the moving member. Motion of *D* is resisted by the spring *E*, the tension of which is adjusted by a spring nut not shown in the diagram. The levers *F* and *G* transmit the motion of the governing cylinder to the relay valve *H*, which is of the usual type employed in oil relays. In fact, the only difference between Fig. 34, and the ordinary centrifugal governor with oil relay mechanism is that,

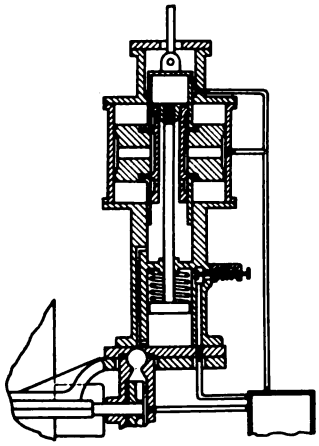

FIG. 36—A SEPARATE PISTON IS PROVIDED FOR CARRYING THE LOAD

in place of the lever *F* being moved by the centrifugal governor, it is controlled by the oil governor cylinder, which receives its oil from the impeller on the turbine shaft. Two impellers are shown in Fig. 34, one on the high-pressure turbine and one on the low-pressure turbine, since this governor is used on a cross-compound, geared, marine turbine. Both impellers discharge into a common line through check valves *B*, so that the speed is controlled by both impellers acting together. In case one of the turbines overspeeds due to any cause, the turbine running at the highest speed would control the speed; the loaded turbine slowing down or stopping and the other running at the normal speed for which the governor is set.

It is obvious that any number of shafts may control the same governor relay mechanism, even though all the shafts run at different speeds, as in the case of some cross-compound marine turbines with geared cruising turbines.

In the case of a number of different speed shafts controlling the same relay, it is only necessary to make the different impellers of such diameters that they all give the same pressure at their respective speeds, or at the speeds at which the various shafts are to take control, as is sometimes required for special applications.

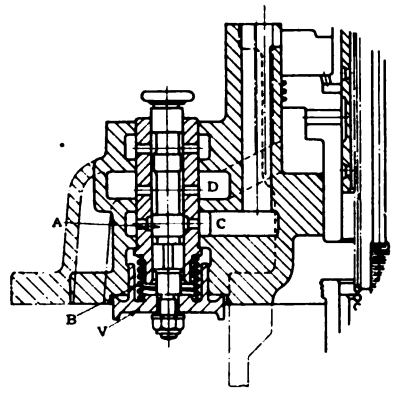


FIG. 37—HODGKINSON'S LOW PRESSURE STOP DEVICE

The first governor employing air as the medium since that of Parsons, is that illustrated in Fig. 38. It consists of a centrifugal fan mounted on the turbine shaft, which takes air from the atmosphere and delivers it under a slight pressure to the governor operating mechanism, which consists of a cylinder *A*, having two aluminum pistons *B* in parallel. The two pistons are used in parallel because of the small pressure difference available. The air pistons operate against a spring and move a relay valve, which admits oil to the valve operating cylinder. The oil for the relay mechanism is supplied by an independent auxiliary oil pump. This operating mechanism is the same in principle as Fig. 34, except that it is not fitted with the automatic stop tripping cylinder of Fig. 34.

In this arrangement, of course, the tension of the governor spring can be adjusted while the machine is in operation, and less difficulty is encountered with the design of the spring since it is outside of the mechanism. It will be noted further that the spring acts on the piston through a lever ful-

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crumed from the bedplate and an extension rod connected to the governor piston rod. The automatic stop is arranged on an extension of the fan hub in the inlet of the fan.

An oil governor mechanism is shown in Fig. 39 which, in general, is the same as Fig. 34, except that

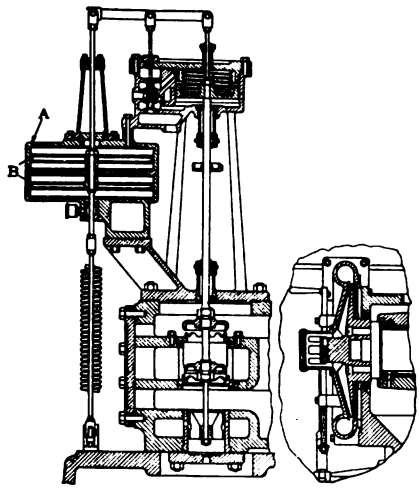

FIG. 38—A GOVERNOR EMPLOYING AIR INSTEAD OF OIL AS A MEDIUM

it is provided with a low inlet pressure, automatic stop relay and the oil relay valve also acts as the oil governing piston and is balanced with the impeller inlet pressure. The relay valve sleeve *K* and spring *S* are as usual, but in this case the oil supply to the operating cylinder does not come through the oil relay valve sleeve.

The oil pressure from the impeller is taken to the governing piston by an independent pipe, as the governor is located at considerable distance from the impeller, and consequently, there are considerable pressure fluctuations in the oil line supplying the operating cylinder. Therefore, if the same oil lines were used to furnish the oil to the governing piston, the latter would be subjected to these pressure fluctuations due to the inertia and friction in the pipes. Since the motion of the governing piston is very slight, by use of a separate supply pipe, all inertia effects are avoided regardless of the distance of the mechanism from the oil impeller.

The follow-up motion of the relay valve sleeve is imparted to it by the floating lever *H*, attached to the operating piston *F* at one end and the fulcrum point on the relay valve bonnet *X* at the other end. The rod *W*, attached to the floating lever *H*, carries the spring shackle nut *E* on its lower threaded portion. The relay valve sleeve always remains in substantially its neutral position. Hence as the operating piston *F* moves upward, carrying the rod *W* with it, the governor spring *S* is slightly elongated, the amount of the elongation being just sufficient to balance the increase in oil pressure due to the change of speed. Since this travel can be made very small, it is evident that no difficulty in designing a suitable spring is encountered in this arrangement. Furthermore the same ideal condition is maintained as in the other relay mechanisms described, of having the relay valve sleeve also act as the governing piston, with nothing to move but itself, so that friction in the lever system has no influence on its sensitiveness.

The low inlet pressure tripping device is shown between the governing relay valve and the operating piston, and operates in the same manner as the trip in Fig. 37, except that in Fig. 39 the operating piston is double acting and, therefore, the trip relay valve changes the connections on both the upper and lower ports of the operating cylinder.

In this arrangement, the speed changer consists of a relief valve *T* which maintains a constant pressure in the chamber *Q* under the relay plunger sleeve,

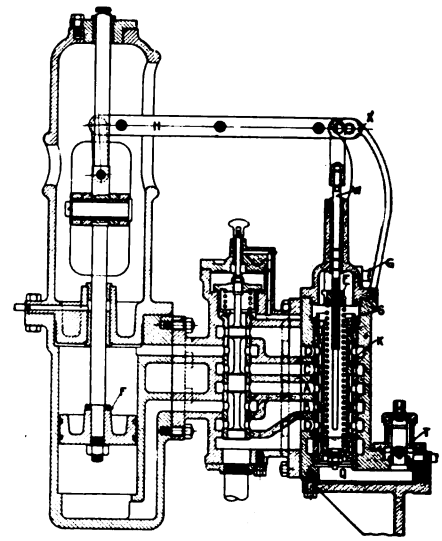

FIG. 39—AN OIL GOVERNING MECHANISM PROVIDED WITH A LOW INLET PRESSURE AUTOMATIC STOP RELAY

*K*. Oil leakage past the relay valve sleeve and through a small orifice maintains a small flow through the chamber *Q*, the pressure of which is determined by the spring loading of the valve *T*. The spring tension is varied by the speed changer motor as desired.

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# Symmetrical Components

## IV—Calculation of Faults on Systems with Lumped Constants (Cont'd)

C. F. WAGNER and R. D. EVANS

IN the preceding articles methods were shown whereby the currents in different parts of a network could be calculated for various types of faults. It was shown how the system could be represented completely by a set of three independent networks representing the three sequences, the manner in which these networks were connected being dependent upon the type of fault. The methods as given applied only to cases in which the fault impedance was of negligible value.

### FAULT IMPEDANCE

In many cases the fault impedance forms a considerable proportion of the total impedance, so that the resultant short-circuit current is much smaller than that which would occur if the fault impedance were zero. In addition, the fault impedance may affect the distribution of the current between the negative and zero phase sequence networks, such as occurs for a double fault to ground. The following discussion shows how the equivalent diagram of the system should be altered to include the fault impedance.

1—*Ground Fault on One Conductor*—The boundary conditions for this type of fault are indicated in Fig. 19 (*A*) in which $\check{Z}$ is the impedance of the fault including the arc, tower footing impedance, etc.

Equations (93) then become:

$$\left.\begin{aligned} \check{e}_x &= \check{Z} I_x \\ I_y &= 0 \\ I_z &= 0 \end{aligned}\right\} \quad \ldots\ldots (116)$$

The current conditions have not been altered, so that the relations between the different sequence currents obtained for $\check{Z} = 0$ still apply. Equation (98), however, showing the relation between the sequence voltages, becomes:

$$\check{e}_x = \check{e}_{x0} + \check{e}_{x1} + \check{e}_{x2} = \check{Z} I_x$$

and since

$$I_x = 3 I_{x1}$$

$$\check{e}_x = 3 \check{Z} I_{x1} \quad \ldots\ldots (117)$$

Equation (102) becomes:

$$\left.\begin{aligned} 3 \check{Z} I_{x1} = \check{e}' &- \Sigma \text{ voltage drops from } e' \text{ to } F \text{ in pos. seq. network} \\ &- \Sigma \text{voltage drops from machine to } F \text{ in neg. seq. network} \\ &- \Sigma \text{voltage drops from machine in zero seq. network} \end{aligned}\right\} \quad \ldots\ldots (118)$$

$$\left.\begin{aligned} e' = {} & \Sigma \text{voltage drops from } e' \text{ to } F \text{ in pos. seq. network} \\ & + \Sigma \text{voltage drops from machine to } F \text{ in neg. seq. network} \\ & + \Sigma \text{voltage drops from machine to } F \text{ in zero seq. network} + 3 \check{Z} I_{x1} \end{aligned}\right\} \quad \ldots\ldots (119)$$

The three networks must therefore be connected to satisfy equations (97) and (119). This will be accomplished by connecting the networks as shown in Fig. 19 (*B*).

2—*Double Fault to Ground*—The boundary conditions and position of fault impedance for this case are indicated in Fig. 20 (*A*). Equations (104) expressing these boundary conditions become:

$$\left.\begin{aligned} \check{e}_y &= \check{Z} (I_y + I_z) \\ \check{e}_z &= \check{Z} (I_y + I_z) = \check{e}_y \\ I_x &= 0 \end{aligned}\right\} \quad \ldots\ldots (120)$$

Applying these relations, equations (105) become

$$\left.\begin{aligned} \check{e}_{x0} &= 1/3 (\check{e}_x + 2 \check{e}_y) \\ \check{e}_{x1} &= 1/3 [\check{e}_x + (a^2 + a) \check{e}_y] = 1/3 (\check{e}_x - \check{e}_y) \\ \check{e}_{x2} &= 1/3 [\check{e}_x + (a^2 + a) \check{e}_y] = 1/3 (e_x - e_y) \end{aligned}\right\} \quad \ldots\ldots (121)$$

These equations supply two voltage conditions which must be satisfied

$$\check{e}_{x2} = \check{e}_{x1} \quad \ldots\ldots (122)$$

$$\check{e}_{x0} - \check{e}_{x1} = \check{e}_y = \check{Z} (I_y + I_z) \quad \ldots\ldots (123)$$

The voltage $\check{e}_y$ from equation (123) may be

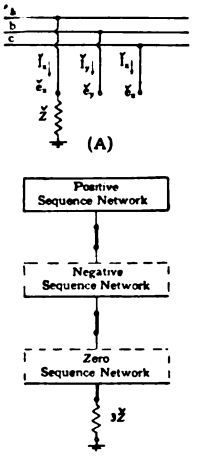


FIG. 19

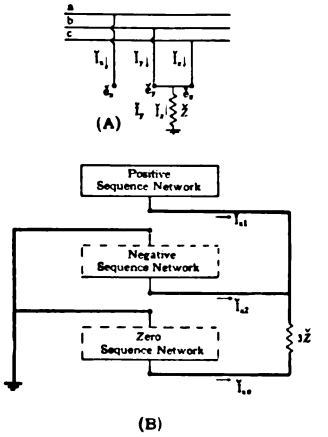


FIG. 20

evaluated in terms of sequence components of currents as follows:

$$I_y = I_{x0} + a^2 I_{x1} + a I_{x2}$$

$$I_z = I_{x0} + a I_{x1} + a^2 I_{x2}$$

Adding

$$I_y + I_z = 2 I_{x0} + (a^2 + a) (I_{x1} + I_{x2}) \quad \ldots\ldots (124)$$

Now from the last of equations (120)

$$I_x = I_{x0} + I_{x1} + I_{x2} = 0 \quad \ldots\ldots (125)$$

and

$$I_{x1} + I_{x2} = -I_{x0}$$

Substituting this relation in (124)

$$I_y + I_z = 3 I_{x0} \quad \ldots\ldots (126)$$

and (123) becomes

$$\check{e}_{x0} - \check{e}_{x1} = 3 \check{Z} I_{x0} \quad \ldots\ldots (127)$$

Now since the three networks are sufficient in themselves, but their manner of connection is dependent upon the boundary condition, the necessary and sufficient conditions to be met by the equivalent networks are those expressed by equations (122), (125), and (127). These conditions are satisfied when the networks are connected as shown in Fig. 20 (*B*).

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3—*Single-Phase Line-to-Line Fault*—The conditions for this particular fault are indicated in Fig. 21 (*A*). Expressed mathematically they are:—

$$\left.\begin{aligned} I_x &= 0 \\ I_y &= -I_z \\ \check{e}_y &= \check{e}_z - \check{Z} I_z \end{aligned}\right\} \quad \text{.....(128)}$$

Since the current relations are unaltered, equations (109), (110), and (111), still apply. From equation (110)

$$I_z = \frac{3}{-a+a^2} I_{x1}$$

so that

$$\check{e}_y = \check{e}_z - \frac{3}{-a+a^2} I_{x1} \quad \text{.....(129)}$$

From the fundamental relations expressed in equations (112) which connect the phase and the sequence quantities

$$\check{e}_{x1} - \check{e}_{x2} = (a-a^2)\,\check{e}_y + (a^2-a)\,\check{e}_z$$

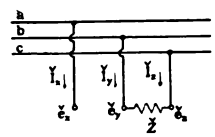
Substituting $\check{e}_y$ from equation (129)

$$\begin{aligned} \check{e}_{x1} - \check{e}_{x2} &= (a-a^2)\,\check{e}_z - \frac{3(a-a^2)\check{Z}}{-a+a^2} I_{x1} + (a^2-a)\,\check{e}_z \\ &= 3\check{Z} I_{x1} \end{aligned} \quad \text{.....(130)}$$

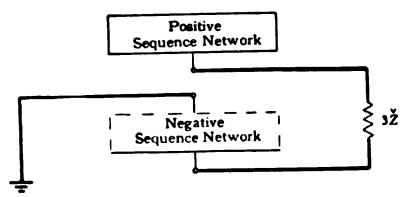
From equations (111) and (130) the two necessary and sufficient conditions which must be met are

$$\left.\begin{aligned} I_{x2} &= -I_{x1} \\ \check{e}_{x1} &= \check{e}_{x2} + 3\check{Z} I_{x1} \end{aligned}\right\} \quad \text{.....(131)}$$

These are satisfied by the connection shown in Fig. 21 (*B*).




(A)




(B)

FIG. 21

## SHORT-CIRCUIT OF GENERATORS

To illustrate the application of the more general relations which have been developed, a simple analytical example will be considered. For this purpose let it be desired to determine the voltages and currents during the short-circuit at the terminals of a symmetrical star-connected generator under different types of unbalanced faults. The impedances to positive, negative and zero sequence currents will be $\check{Z}_1$, $\check{Z}_2$ and $\check{Z}_0$, respectively. This particular example was chosen not only because it is an interesting problem in itself, but also because it furnishes the simplest or elemental form of network which still retains unequal and finite impedances to the three sequences.

1—*Fault to Neutral*—The equivalent diagram for this condition is illustrated in Fig. 22. As can be seen, the currents of the three sequences are all equal to

$$I_1 = I_2 = I_0 = \frac{\check{e}}{\check{Z}_1 + \check{Z}_2 + \check{Z}_0} \quad \text{.....(132)}$$

The current in phase *a*, i.e., the short-circuit current, is

$$\begin{aligned} I_a &= (I_0 + I_1 + I_2) \\ &= \frac{3\check{e}}{\check{Z}_1 + \check{Z}_2 + \check{Z}_0} \end{aligned} \quad \text{.....(133)}$$

$$\begin{aligned} I_b &= I_0 + a^2 I_1 + a I_2 \\ &= (1 + a^2 + a)\, I_{a1} = 0 \\ I_c &= I_0 + a I_1 + a^2 I_2 \\ &= (1 + a + a^2)\, I_{a1} = 0 \end{aligned}$$

The positive sequence component of the terminal

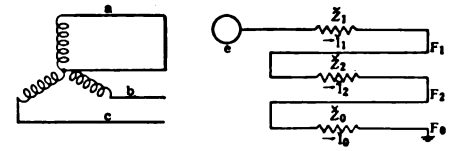



FIG. 22

voltage is the voltage between $F_1$ and $F_0$, viz.,

$$\check{e}_1 = \check{e} - \check{Z}_1 I_1$$

After substituting the value of $I_1$ from (132),

$$\check{e}_1 = \left[1 - \frac{\check{Z}_1}{\check{Z}_1 + \check{Z}_2 + \check{Z}_0}\right] \check{e} \text{ or } \frac{\check{Z}_2 + \check{Z}_0}{\check{Z}_1 + \check{Z}_2 + \check{Z}_0}\,\check{e} \quad \text{.....(134)}$$

Similarly the negative and zero sequence voltages are

$$\begin{aligned} \check{e}_2 &= -\check{Z}_2 I_2 \\ &= -\frac{\check{Z}_2}{\check{Z}_1 + \check{Z}_2 + \check{Z}_0}\,\check{e} \end{aligned} \quad \text{.....(135)}$$

and

$$\begin{aligned} \check{e}_0 &= -\check{Z}_0 I_0 \\ &= -\frac{\check{Z}_0}{\check{Z}_1 + \check{Z}_2 + \check{Z}_0}\,\check{e} \end{aligned} \quad \text{.....(136)}$$

The voltage of phase *a* is then

$$\begin{aligned} \check{e}_a &= \check{e}_0 + \check{e}_1 + \check{e}_2 \\ &= \check{e}\,\frac{\check{Z}_2 + \check{Z}_0 - \check{Z}_2 - \check{Z}_0}{\check{Z}_1 + \check{Z}_2 + \check{Z}_0} = 0 \end{aligned}$$

and of phase *b*

$$\begin{aligned} \check{e}_b &= \check{e}_0 + a^2 \check{e}_1 + a\,\check{e}_2 \\ &= a^2 \check{e} - \frac{\check{e}}{\check{Z}_1 + \check{Z}_2 + \check{Z}_0}(\check{Z}_0 + a^2\check{Z}_1 + a\check{Z}_2) \\ &= \frac{\check{e}}{\check{Z}_1 + \check{Z}_2 + \check{Z}_0}\left[(a^2 - a)\check{Z}_2 + (a^2 - 1)\,Z_0\right] \end{aligned} \quad \text{.....(137)}$$

$$\begin{aligned} \check{e}_c &= \check{e}_0 + a\,\check{e}_1 + a^2 \check{e}_2 \\ &= a\,\check{e} - \frac{\check{e}}{\check{Z}_1 + \check{Z}_2 + \check{Z}_0}(\check{Z}_0 + a\check{Z}_1 + a^2\check{Z}_2) \\ &= \frac{\check{e}}{\check{Z}_1 + \check{Z}_2 + \check{Z}_0}\left[(a - a^2)\check{Z} + (a - 1)\check{Z}_0\right] \end{aligned} \quad \text{.....(138)}$$

2—*Double Fault to Neutral*—The equivalent diagram for this case reduces to that shown in Fig. 23. The solution of this network gives

$$I_1 = \frac{\check{e}}{\check{Z}_1 + \dfrac{\check{Z}_0 \check{Z}_2}{\check{Z}_0 + \check{Z}_2}} = \frac{(\check{Z}_0 + \check{Z}_2)}{\check{Z}_0\check{Z}_1 + \check{Z}_1\check{Z}_2 + \check{Z}_2\check{Z}_0}\,\check{e} \quad \text{.....(139)}$$

$$\begin{aligned} I_2 &= -\frac{\check{Z}_0}{\check{Z}_0 + \check{Z}_2} I_1 \\ &= -\frac{\check{Z}_0}{\check{Z}_0\check{Z}_1 + \check{Z}_1\check{Z}_2 + \check{Z}_2\check{Z}_0}\,\check{e} \end{aligned} \quad \text{.....(140)}$$

$$I_0 = -\frac{\check{Z}_2}{\check{Z}_0\check{Z}_1 + \check{Z}_1\check{Z}_2 + \check{Z}_2\check{Z}_0}\,\check{e} \quad \text{.....(141)}$$

From which

$$I_a = I_0 + I_1 + I_2$$

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$$= \frac{\check{e}}{\check{Z}_0\check{Z}_1 + \check{Z}_1\check{Z}_2 + \check{Z}_2\check{Z}_0}\left[-\check{Z}_2 + \check{Z}_0 + \check{Z}_2 - \check{Z}_0\right] = 0$$

$$\check{I}_b = \check{I}_0 + a^2\check{I}_1 + a\check{I}_2$$

$$= \frac{\check{e}}{\check{Z}_0\check{Z}_1 + \check{Z}_1\check{Z}_2 + \check{Z}_2\check{Z}_0}\left[-\check{Z}_2 + a^2(\check{Z}_0 + \check{Z}_2) - a\check{Z}_0\right]$$

$$= \frac{\check{e}}{\check{Z}_0\check{Z}_1 + \check{Z}_1\check{Z}_2 + \check{Z}_2\check{Z}_0}\left[(a^2-1)\check{Z}_2 + (a^2-a)\check{Z}_0\right] \quad \text{.....(142)}$$

$$\check{I}_c = \check{I}_0 + a\check{I}_1 + a^2\check{I}_2$$

$$= \frac{\check{e}}{\check{Z}_0\check{Z}_1 + \check{Z}_1\check{Z}_2 + \check{Z}_2\check{Z}_0}\left[-\check{Z}_2 + a(\check{Z}_0 + \check{Z}_2) - a^2\check{Z}_0\right]$$

$$= \frac{\check{e}}{\check{Z}_0\check{Z}_1 + \check{Z}_1\check{Z}_2 + \check{Z}_2\check{Z}_0}\left[(a-1)\check{Z}_2 + (a-a^2)\check{Z}_0\right] \quad \text{....(143)}$$

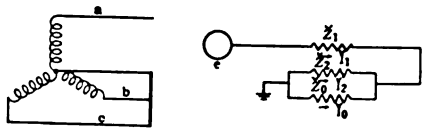


FIG. 23

Since the three sequence components of terminal voltage are equal, i.e.,

$$\check{e}_1 = \check{e}_2 = \check{e}_0 \quad \text{.....(144)}$$

and

$$\check{e}_2 = -\check{I}_2\check{Z}_2$$

$$= \check{e}\frac{\check{Z}_0\check{Z}_2}{\check{Z}_0\check{Z}_1 + \check{Z}_1\check{Z}_2 + \check{Z}_2\check{Z}_0} \quad \text{.....(145)}$$

then

$$\check{e}_a = 3\check{e}_2$$

$$= 3\check{e}\frac{\check{Z}_0\check{Z}_2}{\check{Z}_0\check{Z}_1 + \check{Z}_1\check{Z}_2 + \check{Z}_2\check{Z}_0} \quad \text{.....(146)}$$

3—*Single Phase Line to Line Fault*—The circuit condition to which this case reduces is shown in Fig. 24.

$$\check{I}_1 = \frac{\check{e}}{\check{Z}_1 + \check{Z}_2} \quad \text{.....(147)}$$

$$\check{I}_2 = -\frac{\check{e}}{\check{Z}_1 + \check{Z}_2} \quad \text{.....(148)}$$

$$\check{I}_0 = 0$$

Therefore

$$\check{I}_a = \check{I}_0 + \check{I}_1 + \check{I}_2$$

$$= 0 + \frac{\check{e}}{\check{Z}_1 + \check{Z}_2} - \frac{\check{e}}{\check{Z}_1 + \check{Z}_2} = 0$$

$$\check{I}_b = \check{I}_0 + a^2\check{I}_1 + a\check{I}_2$$

$$= 0 + a^2\frac{\check{e}}{\check{Z}_1 + \check{Z}_2} - a\frac{\check{e}}{\check{Z}_1 + \check{Z}_2}$$

$$= (a^2 - a)\frac{\check{e}}{\check{Z}_1 + \check{Z}_2} \quad \text{.....(149)}$$

$$\check{I}_c = \check{I}_0 + a\check{I}_1 + a^2\check{I}_2$$

$$= 0 + a\frac{\check{e}}{\check{Z}_1 + \check{Z}_2} - a^2\frac{\check{e}}{\check{Z}_1 + \check{Z}_2}$$

$$= (a - a^2)\frac{\check{e}}{\check{Z}_1 + \check{Z}_2} = -\check{I}_b \quad \text{.....(150)}$$

Also

$$\check{e}_1 = \check{e}_2 = -\check{Z}_2\check{I}_2$$

$$= \frac{\check{Z}_2}{\check{Z}_1 + \check{Z}_2}\check{e} \quad \text{.....(151)}$$

Therefore

$$\check{e}_a = \check{e}_0 + \check{e}_1 + \check{e}_2$$

$$= \frac{2\check{Z}_2}{\check{Z}_1 + \check{Z}_2}\check{e} \quad \text{.....(152)}$$

$$\check{e}_b = \check{e}_0 + a^2\check{e}_1 + a\check{e}_2$$

$$= \frac{(a^2 + a)\check{Z}_2}{\check{Z}_1 + \check{Z}_2}\check{e}$$

$$= -\frac{\check{Z}_2}{\check{Z}_1 + \check{Z}_2}\check{e} \quad \text{.....(153)}$$

$$\check{e}_c = \check{e}_0 + a\check{e}_1 + a^2\check{e}_2$$

$$= \frac{(a + a^2)\check{Z}_2}{\check{Z}_1 + \check{Z}_2}\check{e} = \check{e}_b \quad \text{.....(154)}$$

NUMERICAL EXAMPLE OF GENERATOR FAULTS

To aid in a more thorough understanding of the different types of generator faults, calculations will be made of a concrete machine for sustained short circuits. Consider a machine in which

$\check{Z}_1 = 0 + j\,1.0$ (synchronous impedance)
$\check{Z}_2 = 0.1 + j\,0.3$ (imped. to neg. seq. current)
$\check{Z}_0 = 0 + j\,0.1$ (imped. to zero seq. current)
and $\check{e} = 100 + j\,0$

1—*Fault to Neutral in Phase a*—Referring to Fig. 22.

$$\check{I}_0 = \check{I}_1 = \check{I}_2 = \frac{100}{\check{Z}_0 + \check{Z}_1 + \check{Z}_2} \quad \frac{100}{0.1 + j\,1.4}$$

$$= 5.08 - j\,71.1$$

$$\check{I}_a = \check{I}_0 + \check{I}_1 + \check{I}_2 = 3\,(5.08 - j\,71.1)$$

$$= 15.24 - j\,213.3$$

$$\check{e}_1 = \check{e} - \check{I}_1\check{Z}_1$$

$$= 100 - j\,1.0\,(5.08 - j\,71.1)$$

$$= 28.9 - j\,5.08$$

$$\check{e}_2 = -\check{I}_2\check{Z}_2$$

$$= -(5.08 - j\,71.1)\,(0.1 + j\,0.3)$$

$$= 21.84 + j\,5.59$$

$$\check{e}_0 = -\check{I}_0\check{Z}_0$$

$$= -(5.08 - j\,71.1)\,(0 + j\,0.1)$$

$$= -7.11 - j\,0.508$$

$$\check{e}_b = \check{e}_0 + a^2\check{e}_1 + a\check{e}_2$$

$$= (-7.11 - j\,0.508) + (-0.5 - j\,0.866)\,(+28.9 - j\,5.08)$$

$$+ (-0.5 + j\,0.866)\,(-21.84 + j\,5.59)$$

$$= (-7.11 - j\,0.508) + (-18.85 - j22.49) + (6.08 - j\,21.70)$$

$$= -19.88 - j\,44.70$$

$$\check{e}_c = \check{e}_0 + a\check{e}_1 + a^2\check{e}_2$$

$$= (-7.11 - j\,0.508) + (-0.5 + j\,0.866)\,(+28.9 - j\,5.08)$$

$$+ (-0.5 - j\,0.866)\,(-21.84 + j\,5.59)$$

$$= (-7.11 - j\,0.507) + (-10.05 + j\,27.57) + (15.76 + j\,16.1)$$

$$= -1.40 + j\,43.16$$

2—*Double Fault to Neutral*—For this case referring to Fig. 23.

$$\frac{\check{Z}_0\check{Z}_2}{\check{Z}_0 + \check{Z}_2} = \frac{j\,0.1\,(0.1 + j\,0.3)}{j0.1 + 0.1 + j\,0.3}$$

$$= \frac{-0.03 + j\,0.01}{0.1 + j\,0.4}$$

$$= 0.00588 + j0.0765$$

$$\check{I}_1 = \frac{\check{e}}{\check{Z}_1 + \frac{\check{Z}_0\check{Z}_2}{\check{Z}_0 + \check{Z}_2}}$$

$$= \frac{100}{j1.0 + 0.00588 + j0.0765}$$

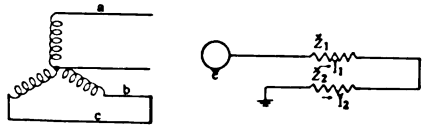


FIG. 24

$$= \frac{100}{0.00588 + j1.0765}$$

$$= 0.50 - j\,92.8$$

$$\check{I}_2 = -\frac{\frac{\check{Z}_0\check{Z}_2}{\check{Z}_0 + \check{Z}_2}}{\check{Z}_2}\check{I}_1$$

$$= \frac{-(0.00588 + j0.0765)}{0.1 + j\,0.3}(0.50 - j92.8)$$

$$= -5.581 + j\,21.81$$

$$\check{I}_0 = -\frac{\frac{\check{Z}_0\check{Z}_2}{\check{Z}_0 + \check{Z}_2}}{\check{Z}_0}\check{I}_1$$

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$$= \frac{-(0.00588 + j0.0765)}{+j0\,1}\,(0.50 - j\,92.8)$$
$$= 5.07 + j\,71.02$$

Combining the sequence components, the following phase currents are obtained:

$$\dot{I}_a = 0$$
$$\dot{I}_b = \dot{I}_0 + a^2\dot{I}_1 + a\dot{I}_2$$
$$= (5.07 + j\,71.02) + (-0.5 - j.866)\,(0.50 - j\,92.8) + (-.5 + j.866)\,(-5.581 + j\,21.81)$$
$$= -91.64 + j\,58.38$$
$$\dot{I}_c = \dot{I}_0 + a\dot{I}_1 + a^2\dot{I}_2$$
$$= (5.07 + j\,71.02) + (-0.5 + j.866)\,(0.5 - j\,92.8) + (-0.5 - j.866)\,(-5.581 + j\,21.81)$$
$$= 106.85 + j\,154.65$$
$$\check{e}_1 = \check{e}_2 = \check{e}_0$$
$$\check{e}_2 = -\check{Z}_0\dot{I}_0$$
$$= -j\,0.1\,(5.07 + j\,71.02)$$
$$= 7.10 - j\,0.507$$
$$e_a = 3\,e_2$$
$$= 3\,(7.101 - j\,0.507)$$
$$= 21.3 - j\,1.521$$

3—*Single Phase Line to Line Fault*—Referring to Fig. 24.

$$\dot{I}_1 = \frac{\check{e}}{\check{Z}_1 + \check{Z}_2}$$
$$= \frac{100}{j\,1 + 0.1 + j\,0.3}$$
$$= 5.88 - j\,76.5$$
$$\dot{I}_2 = -\dot{I}_1$$
$$= -5.88 + j\,76.5$$
$$\dot{I}_0 = 0$$
$$\dot{I}_a = \dot{I}_0 + \dot{I}_1 + \dot{I}_2 = 0$$
$$\dot{I}_b = \dot{I}_0 + a^2\dot{I}_1 + a\dot{I}_2 = 0 + (a^2 - a)\,\dot{I}_1$$
$$= -j1.732\,\frac{\check{e}}{\check{Z}_1 + \check{Z}_2} = -j1.732\,(5.88 - j\,76.5)$$
$$= -132.5 - j\,10.2$$
$$\dot{I}_c = \dot{I}_0 + a\dot{I}_1 + a^2\dot{I}_2 = 0 + (a - a^2)\,\dot{I}_1 = -\dot{I}_b$$
$$= 132.5 + j\,10.2$$
$$\check{e}_1 = \check{e}_2 = -\check{Z}_2\dot{I}_2$$
$$= -(0.1 + j\,0.3)\,(-5.88 + j\,76.5)$$
$$= 23.54 - j\,5.89$$
$$\check{e}_0 = 0$$
$$\check{e}_a = \check{e}_0 + \check{e}_1 + \check{e}_2$$
$$= 0 + 2\,(23.539 - j\,5.886)$$
$$= 47.08 - j\,11.76$$
$$\check{e}_b = \check{e}_0 + a^2\check{e}_1 + a\,\check{e}_2$$
$$= 0 + (a^2 + a)\,\check{e}_1 = -\check{e}_1$$
$$= -23.54 + j\,5.89$$
$$\check{e}_c = \check{e}_0 + a\,\check{e}_1 + a^2\,\check{e}_2$$
$$= 0 + (a + a^2)\,\check{e}_1 = -\check{e}_1$$
$$= -23.54 + j\,5.89$$

*(To Be Continued)*

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# Graphical Flux Mapping

## IV—Non-Salient Pole Synchronous Machines (Cont'd)

J. F. CALVERT and A. M. HARRISON

The first article of this series, which appeared in the March, 1928, issue of the JOURNAL, gave a fundamental principle for graphically determining magnetic fields, and illustrated this method with a few simple examples. In the two subsequent issues, the fields of turbine generators were discussed in some detail. Drawings were shown for the case where only the rotor winding was excited, and then figures were presented which illustrated the magnetic conditions where the stator winding was excited alone. In the present article, the flux distributions in this type of machine are discussed when both rotor and stator windings are excited.

CERTAIN approximations are necessary in plotting the end zone fields, necessitated by the fact that the distribution is three dimensional, and the theory is strictly applicable only to two dimensional figures. It has been found necessary to limit the efforts in end zone mapping to the axial plane through the maximum magnetomotive forces. Consequently, when plotting the resultant end zone fields established by both windings, the only cases which can be drawn are those in which these centerplanes coincide, namely, the zero percent power-factor conditions, under or over-excited. As the latter condition shows the greater variation from fields of either one alone, it will be considered first. Before proceeding to the actual machine, however, the more simple case of an air-core machine, Fig. 32, will be used to illustrate certain rather fundamental characteristics of this type of field.

*A Machine Without Iron Parts*—The flux distribution in a plane at right angles to the two coils will be about as shown in Fig. 33, when the field

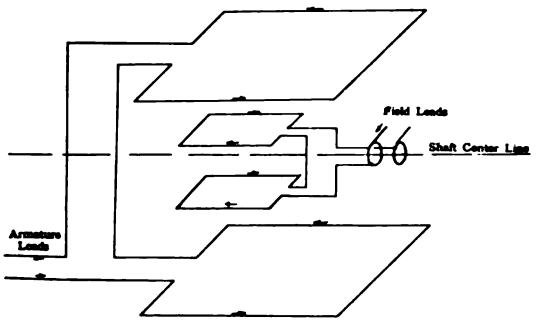


FIG. 32—A DIAGRAMMATIC SKETCH OF AN AIR-CORE MACHINE

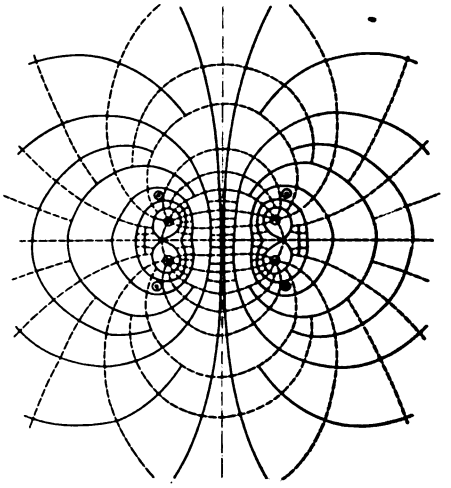

FIG. 33—FLUX DIAGRAM OF AN AIR-CORE MACHINE WITH THE FIELD ALONE EXCITED

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is excited alone. This distribution will be approximately correct in either an axial plane through the coils and shaft or in a radial plane through the coils. The field m.m.f. is 12 units. The flux distribution in the same plane, due to the armature alone, is shown in Fig. 34. The armature m.m.f. is 5 units.

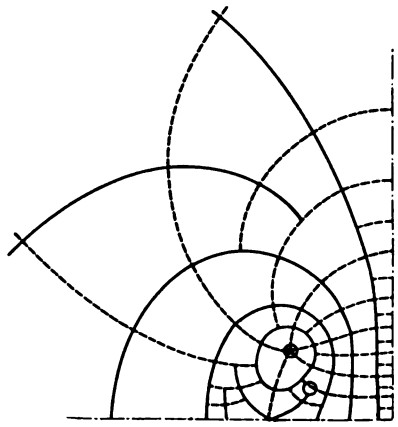

FIG. 34—FLUX DIAGRAM OF AN AIR-CORE MACHINE WITH THE ARMATURE ALONE EXCITED

In these two figures, the following conventional divisions of the flux can readily be discerned: In Fig. 33, when the field is excited alone, the air-gap flux must be that which links the armature coils as well as the field, and the field leakage flux must be that which links the field but not the armature. In Fig. 34, the armature demagnetizing flux is that which links the field coils when only the armature is excited. The armature leakage flux is that which links the armature, but not the field.

The flux distribution is shown in Fig. 35 when

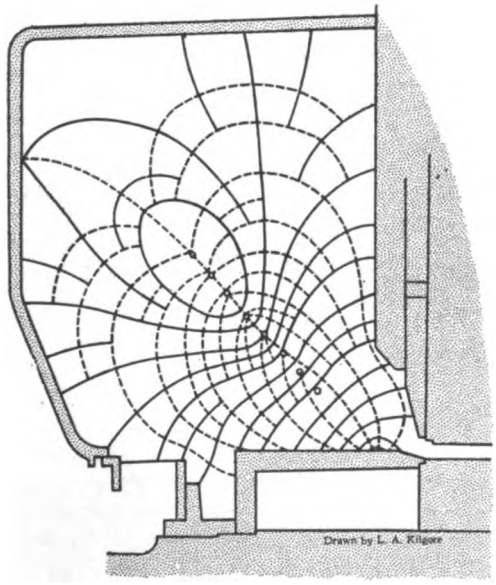


FIG. 36—END ZONE FLUX DISTRIBUTION OF A TURBINE GENERATOR WITH BOTH THE ROTOR AND STATOR EXCITED

The retaining ring flux and ampere-turn distribution is assumed to be the same as when only the rotor is excited.

both windings are excited as before, and are magnetically opposed across the air-gap. The m.m.f. ratios of field to armature are as 12 to 5. There are two features to be noticed which are of fairly general application in that they will hold true in commercial machines in the end zones in spite of the redistribution of the field effected by the iron parts.

The First Point is: Since the field m.m.f. is stronger than that of the armature, there is some point outside of both windings beyond which the field must predominate. The air-gap flux must link

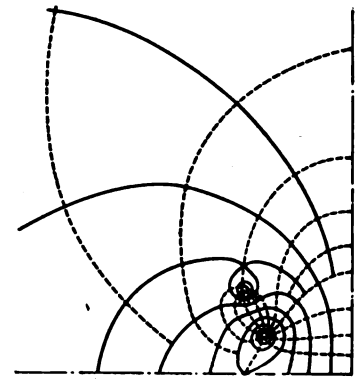

FIG. 35—FLUX DIAGRAM OF AN AIR-CORE MACHINE WITH BOTH THE ARMATURE AND FIELD EXCITED

both windings and envelop a certain loop of flux about the armature coil. Within this loop, the flux threads the armature winding in the reverse direction to the greater portion of the air-gap flux. The first line which links both windings must just touch this reverse flux loop at one point. These conditions must exist in both the radial and in the axial planes of the air-core machine.

The Second Point is: Between the armature and field conductors, the flux travels in the same direction as both the field leakage and the armature leakage of Figs. 33 and 34. Some of this flux actu-

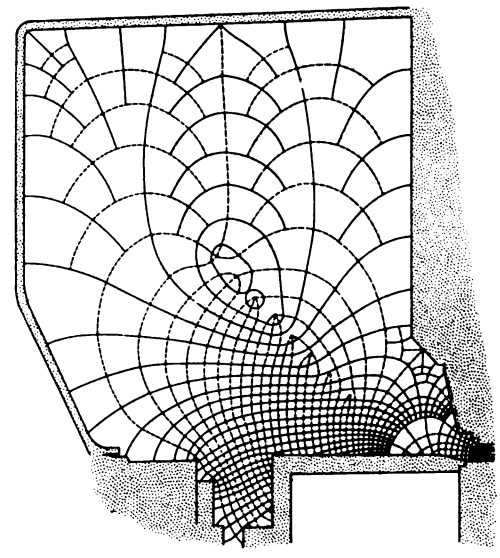

FIG. 37—CORRECTED FLUX DISTRIBUTION

An attempt has been made to correct Fig. 36 for the effect of the armature winding on the m.m.f. distribution in the retaining ring.

ally goes through the armature winding outwardly, and then turns back to pass between the windings without actually linking the armature winding.

*End Zone Flux*—The foregoing points are particularly applicable to the end zone conditions in

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FIG. 38—A PHOTOGRAPH OF AN ACTUAL FILING MAP OF THE COMBINED FIELD SHOWN IN FIGS. 36 AND 37

the commercial turbine generators, because the fields are produced by somewhat similarly arranged conductors and produce a somewhat similar distribution of flux. This is true in the radial center plane of the poles in Fig. 36. Since the flux loop, within which the armature alone is predominant, just touches the end bell surface, the rotor winding is predominant not only in the core, but also in the end bell iron. This conclusion is borne out by compass readings made on the outside surface of the bell when both windings are excited. The field on this iron part has the same direction and can hardly be

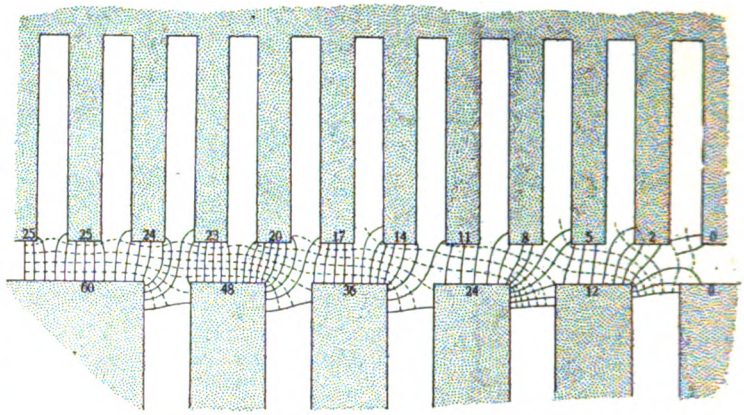


FIG. 39—FLUX DISTRIBUTION IN THE AIR-GAP AT FULL LOAD, ZERO POWER-FACTOR OVER-EXCITED

distinguished from that due to the rotor winding alone.

In drawing Fig. 36, the armature winding m.m.f's are assumed to be as shown in Fig. 30. The field current and m.m.f. distribution in the retaining ring is the same as that shown in Figs. 22 and 23* for flux distribution when the rotor alone is excited.

In Fig. 36 no allowance has been made for the effect of the armature winding in increasing the retaining ring flux. An estimate was made based on Fig. 36 and the field redrawn as in Fig. 37. The true condition is probably somewhere between these two. Fig. 38 shows this distribution as determined by iron filings.

*Flux Distribution in the Air-Gap*—Fig. 39 shows the air-gap distribution for the full-load, zero percent power-factor, over-excited condition. The m.m.f.

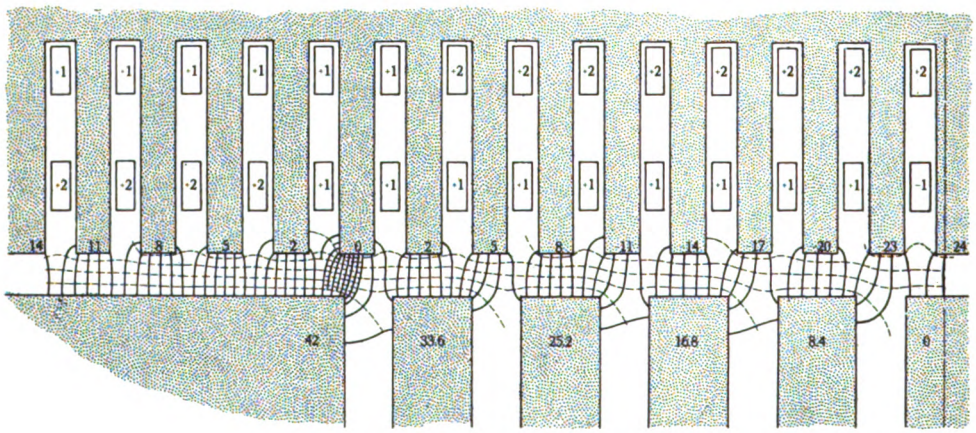


FIG. 40—FLUX DISTRIBUTION IN THE AIR-GAP AT THE FULL LOAD UNITY POWER-FACTOR CONDITION —LEFT HALF

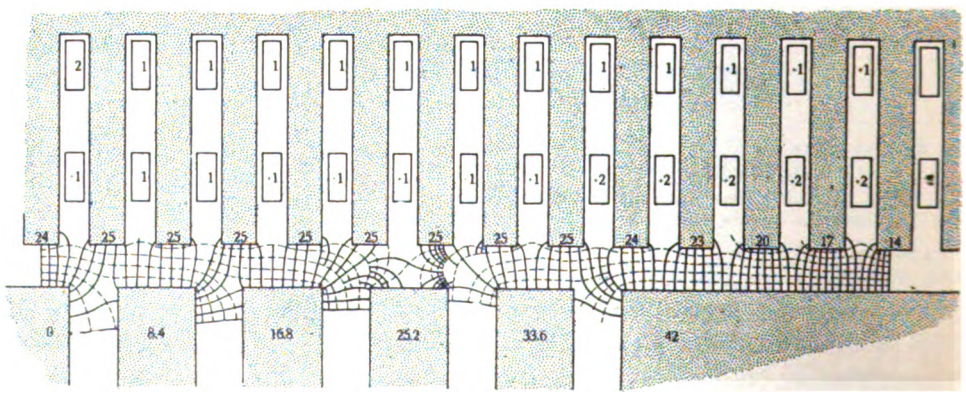


FIG. 41—FLUX DISTRIBUTION IN THE AIR-GAP AT THE FULL LOAD UNITY POWER-FACTOR CONDITION—RIGHT HALF

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values due to the field alone, Figs. 16 and 17,* and the armature alone, Fig. 26, are superposed for the combined or resultant field. No saturation and no damping currents have been considered. As before, the differences in the numbers on the iron parts along the air-gap give the relative m.m.f's between the corresponding surfaces in the directions from the higher toward the lower numbers.

*In the JOURNAL for April '28, p. 182.

Figures 40 and 41 show the air-gap distribution at the 100 percent power-factor over-excited condition. The two halves of the pole pitch are not the same in this case, and hence this larger field plot is required. This type of field mapping was made use of recently in the analysis of a trouble job on a large turbine generator.**

**"A Practical Application of Graphical Flux Mapping" —in the JOURNAL for Nov., 1927, p. 543.

(*To be Continued*)

# Methods of Lapping Tape

A. C. ROE

INSULATING tape may be lapped when applied to stator, rotor, and field coils in five different ways. The method of lapping and the width of the tape used has considerable effect on the finished surface.

First is the half lapped, or half overlapped method. These terms are derived from the fact that in applying the tape, each succeeding turn is put on by guiding the left hand side of the tape along the center line of the turn preceding it, the tape being applied left to right. When the coil is taped, it has a scale effect, the width of the scale being equal to one half the width of the tape used.

A section of a bar taped in this manner with ¾ in. wide material and half lapped is shown in Fig. 1, the full description being "one layer of 0.007 by ¾ in. cotton tape, half overlapped." At the right of Fig. 1, the end of the tape indicates the position for starting the next turn. In practice, the edge of the preceding turn shows through the turn that is fully visible and acts as a guide for the next turn.

An exact and true half lap is practically impossible to obtain, the variation being from 1/64 to 1/8 in. less than half lapped, depending on the skill and care of the operator.

Half lapping provides a wall thickness of material equivalent to twice the thickness of the tape and, if the lapping is done with care, it can be considered as a double thickness of material. If the lapping is spread out, there will be sections in each turn of tape where there is only one thickness of material, the width of these sections depending on the departure from a true half lap. Thus a close half lap is of importance when used to separate two or more adjacent turns or conductors, as on the individual coils or bars of strap copper coils.

Half lapping without leaving wrinkles in the tape, becomes more difficult as the thickness of the tape increases. This is due to the method of progression which is commonly in a saw tooth form. That is, on one side the tape starts and slants in the direction of application, and on the opposite side the tape drops straight down, and as the next turn of tape must start on an edge that has different widths, as at the right end of the bar in Fig. 1, it follows that a true pitch is hard to form. Thus there is a tendency to wrinkle, which increases with the thickness, and width of the material used. The saw tooth effect is more pronounced on rectangular sections than with round or square objects.

The width and thickness of the tape also effects the ease of application and wrinkling. The narrow width is easier to apply and forms a tighter lap.

Another method of applying tape is called spaced taping. This is shown in Fig. 2, and consists of leaving a space between each succeeding turn of tape. This adds one thickness per side, and is used only as a binding medium, except where more than one layer is used. In this case the open spaces are covered with the next layer of tape, resulting in a double thickness per side, which is equivalent to one layer of half-lapped tape of the same thickness.

Space taping progresses in a true spiral effect but the wider the tape and the thicker the material the more difficult it is to apply without wrinkles. Also the change from half lapping to spacing, when starting down the slot section of a coil, will cause wrinkles.

The width of the space between turns depends on the application and in general, for exterior use on coils through the slot sections, spacing from 1/16 to 1/8 in. is common. For general binding, ¼ to ⅜ in. spacing is satisfactory, but the material saved should be balanced by the labor cost, as in some cases wide spacing involves more work.

Tape may be edged lapped or slightly overlapped. This is shown in Fig. 3, and consists of overlapping the edges of each succeeding turn of tape 1/32 to 1/8 in. One layer of edged lapped tape is equivalent to one thickness of material, the overlap being used to obtain a seal, thus excluding dirt, etc., and eliminating bare spaces.

Edge taping is more apt to cause wrinkles, as the extra width causes a back lash, throwing the spiral out of line.

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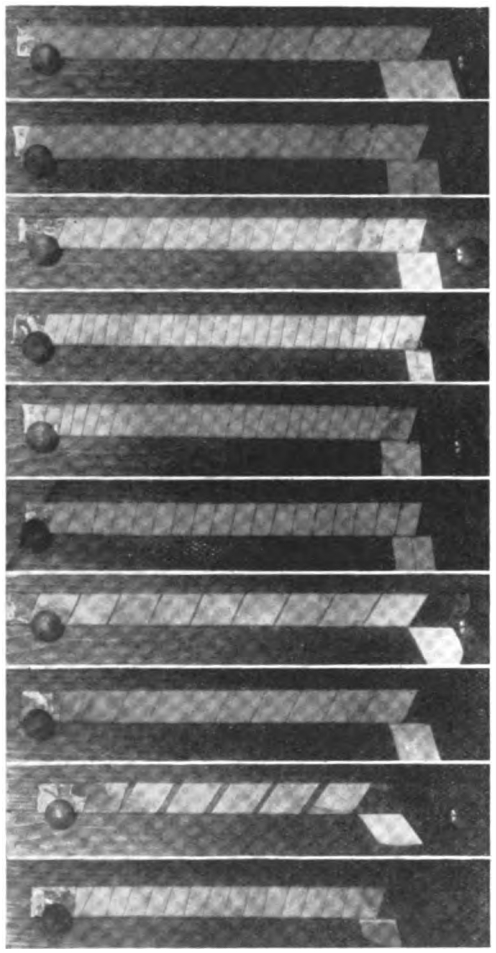
However one turn covers more linear space than half lapping.

A fourth method is called butted. This is shown in Fig. 4, and consists of butting the edges of the turns of tape, so that they neither overlap nor allow spaces between turns. This gives one thickness of material, and is used principally with thick tape, such as asbestos tape, where the thickness of the coil must be kept to a minimum and still obtain the maximum benefit from the material. Butting tape is difficult and slow, and requires a stiff tape that will not distort when applying, it being necessary on important jobs to pick the tape into place. This means a blunt tool or a finger must be used to pull the turn in place so that its edges butt the preceding turn.

Tape may be triple lapped as shown in Fig. 6. Triple lapping consists of applying the tape so that each succeeding




turn covers two-thirds of the preceding turn; or the exposed section is one-third of the total width of the tape. By triple lapping, it is possible to apply the equivalent of three thicknesses of material at one time and obtain a tight seal and lap. It is fairly easy to apply after once getting the knack of judging the one-third spacing.

One method used as a guide to obtain a uniform half lapping consists of running a line or tracer of some dark color, as blue, red, brown, etc., through the center of the tape as shown in Fig. 5. This idea could be used for triple lapping by running a colored tracer one-third of the distance from the left hand edge of the tape.

The width of the tape greatly effects the finish and cost of the coils. The tape width should be selected with the following factors in mind: the kind of lap and seal required; whether the tape is to be applied by hand or machine, the size of coil to be insulated, considering length, width and cross section, and the kind and thickness of the tape. In general, the following points hold true. For small coils such as 5 in. long and wide, ⅛ to ½ in. cross-section, use ½ in. wide tape. For coils up to 24 in. long, 14 to 18 in. wide and of cross-sections larger than above, up to 1 in. and 1½ in., use ¾ in. tape. For larger sizes, use 1 in. wide tape except for machine taping, where ¾ in. tape will be found in most cases to give better results.

For all field coils, 1¼ or 1½ in. tape is best, as these coils generally are of large cross-section. It is difficult to obtain a good lap with narrow tape under these conditions.

The effect of tape width on the lapping is shown in Figs. 7, 8, 9, 10. All these bars are half lapped, the tape increasing ¼ in. in width from ½ to 1¼ in. Half lapping narrow tape, as in Fig. 7 results in a narrow exposed space between turns. This results in a tight seal, which can be proved by taping a bar and trying to pick up the edge of the tape. Thus ½ in. tape half lapped is of value where a tight seal is wanted to exclude moisture, steam or acid fumes, etc.

Tape ¾ in. wide, half lapped is shown in Fig. 8. Notice the width of the lapping as compared to Fig. 7. One inch wide tape is half lapped in Fig. 9 the width of the lap increasing. One and one-fourth in. wide tape half lapped is shown in Fig. 10. As wider tape is used, a wider lap results, which means

TABLE I—EFFECT OF WIDTH ON COST
(Half Lapped)

| Width Inches | Turns | Yards | Cost per yd. Cents | Total cost Dollars |
|---|---|---|---|---|
| ½ | 9600 | 533 | 0.5 | 2 67 |
| ¾ | 6400 | 355 | 0 59 | 2 09 |
| 1 | 4800 | 266 | 0.74 | 1 97 |
| 1¼ | 3840 | 213 | 0.89 | 2 00 |

TABLE I—EFFECT OF TAPE WIDTH ON COST
(Tape spaced ⅛ in.)

| Width Inches | Turns | Yards | Cost per yd. Cents | Total cost Dollars |
|---|---|---|---|---|
| ½ | 3840 | 213 | 0.5 | 1 07 |
| ¾ | 2743 | 152 | 0 59 | 0 90 |
| 1 | 2133 | 118 | 0 74 | 0.87 |
| 1¼ | 1745 | 97 | 0 89 | 0.86 |

that the edge of the tape is easier to pick up, giving a looser seal. However, the wide tape results in a greater creepage distance, which must be considered.

The width of the tape also affects the cost of applications and cost of material, as the following figures will indicate. To obtain the comparative figures, a ½ in. square bar, 200 feet long was used, and a mean length of 2 in. for each turn used. The first tabulation is based on half lapped tape. The second tabulation is based on spacing the tape ⅛ in. apart, using the same bar and mean length of tape per turn.

The cost per yard used in the above tables is not a true price, but the relative increase in price per yard for the different widths is correct, which gives a true picture of the percent variations in costs.

Considering Table 1, we find that the ½ in. tape requires 3200 turns, and 178 yards more than the ¾ in. tape, and the cost of the material is reduced in favor of the ¾ in. tape. Comparing the ¾ in. and 1 in. tape, we find 1600 turns and 89 yards in favor of the 1 in. tape.

Comparing the second table with the first, we find a greater difference, and these tabulations indicate that the width of the tape, cost per yard, method and speed of applying the tape greatly effects the final cost of the coil, and has an important bearing on the quality of the finished coil.

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# How to Refinish or Clean Switchboard Panels

TO change a polished marble panel to black marine, the polish should first be entirely removed by rubbing down with a piece of pumice stone and then the surface should be sprayed with lacquer. During the spraying all apparatus mounted on the panel should be kept covered so that it will not receive the spray.

Black marine finish may be removed from a panel by rubbing with a piece of waste soaked in lacquer thinner.

The finish of black marine slate or steel panels may be cleaned by wiping with a chamois skin which has been immersed in luke warm water and the water rung out. Black marine finished slate or steel may also be cleaned by wiping with slightly oiled waste.

To remove oil stain from polished marble apply a mixture of benzine and plaster of paris, letting it remain on the stain for 48 hours. Then remove it and clean the panel.

# How to Obtain Current and Voltage in Phase from Three-Phase, Three-Wire System

IT is frequently necessary to obtain from a three-phase three-wire system, operating at unity power-factor, current and voltage which are in phase. This is a requirement, for example, for satisfactory operation of a three-phase compensator on a three-phase induction regulator. On a three-phase, three-wire circuit at 100 percent power-factor the current in any wire is 30 degrees out of phase with the voltage taken

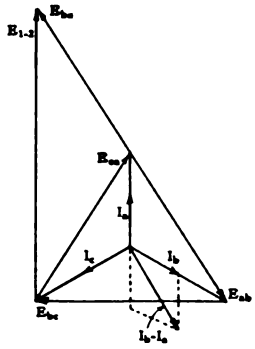

FIG. 1

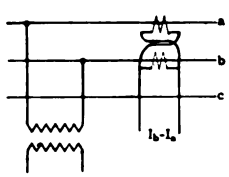

FIG 2

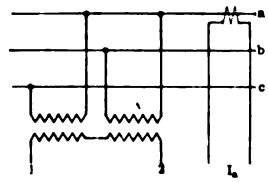

FIG 3

across this wire and one of the other two wires. This is shown vectorially in Fig. 1, $I_c$ being 30 degrees out of phase with $E_{bc}$. However, by connecting two current transformers on each of two wires of a three-phase balanced line and cross connecting the secondaries as shown in Fig. 2, the current and voltage taken off will be in phase. Thus, currents $I_b$ is added to $-I_a$ in Fig. 1 to give $I_b - I_a$ which is in phase with $E_{ab}$, but has a magnitude of three times line current.

It is possible to accomplish the same end with two potential transformers and one current transformer connected as shown in Fig. 3. This scheme of connections produce a voltage at 1-2 in phase with the current transformer secondary. This is done, in Fig. 1, by adding $E_{ca}$ to $E_{ba}$ to give a voltage $E_{1\text{-}2}$ in phase with $I_a$.

It will be noticed that the voltage at terminals 1-2 in Fig. 3 is 1.73 times as great as the voltage at the terminals 1-2 in Fig. 2. Thus, in the two potential transformer method transformers with larger ratios are necessary. In the other scheme, current transformers of similarly larger ratios are required.

Sometimes it is less convenient to use line current and 1.73 times line voltage (three times voltage to neutral) than it is to use three times line current and line voltage. Thus the method to use is one of comparative costs of the voltage and current transformers and the relative convenience of the two methods.

# Two Regulators Have Same Current Capacity as Three

IT IS sometimes suggested that a three-phase circuit be regulated with two single-phase regulators and that when the load increases a third regulator can be added to take care of the increased load, as is frequently done with transformers. This, however, cannot be done. The addition of the third regulator does not increase the current capacity of the equipment, but increases the percent regulation obtainable by approximately 50 percent. For example, two 100 ampere 10 percent regulators will provide 10 percent regulation on a three-phase 100 ampere circuit; and when the third regulator is added the three 10 percent regulators will provide approximately 15 percent regulation on a 100 ampere three-phase circuit.

That three induction regulators do not have any more current carrying capacity than two regulators may be easily seen by contrasting the regulator with the voltage transformer. Two voltage transformers are often connected in open-delta on a three-phase line. The current rating is 58 percent of that of three transformers. However, the voltage of the two is the same as of the three, as full line voltage

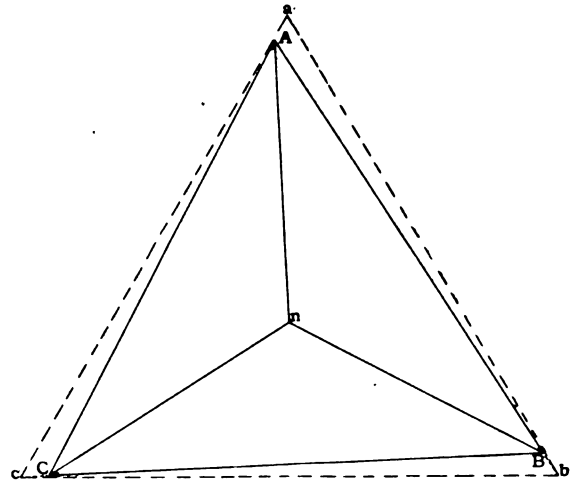

FIG. 1—VECTOR DIAGRAM FOR THREE SINGLE-PHASE REGULATORS ON A THREE-PHASE LINE

(or line to neutral voltage) is impressed on each transformer regardless of the number of other transformers present. Therefore, three transformers on a three-phase system have more current capacity than two, but the voltage is the same. We would expect the opposite to be true of the regulator, since the regulator is essentially a series device and the transformer an across-the-line device. That is, full line current flows through each regulator regardless of the presence of other regulators. Hence, the current carrying capacity of a regulator is determined solely by the line. The voltages which the regulators add to or subtract from the line are independent, as shown in Fig. 1. The regulator for phase $AB$ adds (or subtracts) voltage $E_{Bb}$ to line voltage $E_{AB}$; regulator in phase $BC$ adds voltage $E_{Cc}$ to $E_{BC}$; and regulator in phase $CA$ adds voltage $E_{Aa}$ to $E_{CA}$. The line voltages are shifted at the time of boost from $E_{AB}$, $E_{BC}$ and $E_{CA}$ to $E_{ab}$, $E_{bc}$ and $E_{ca}$.

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## Outdoor Trucks and Housings

THE Commonwealth Edison Company of Chicago in its new switchyard at its Northwest Station has made very effective use of outdoor truck-type oil circuit-breakers and steel housings. By placing each housing in a concrete cell they obtained the switching station shown in Fig. 1, which gives the happy combination of dependability, complete weather protection, maximum safety, pleasing appearance and ease of maintenance. This station provides for seven three-phase,

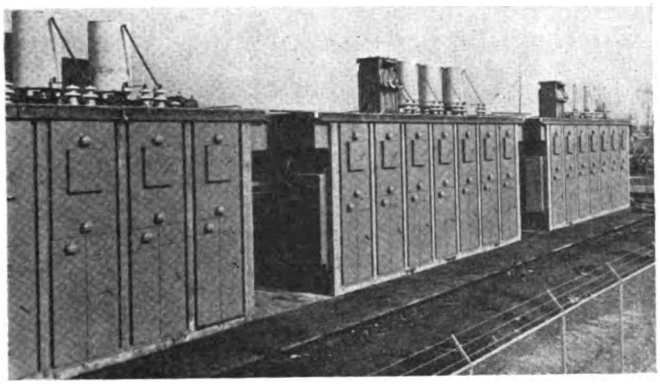

FIG. 1—NEW SWITCHYARD AT THE NORTHWEST STATION OF THE COMMONWEALTH EDISON CO.

12 000 volt feeders All the oil circuit-breakers for one phase are grouped together as shown, with adequate spacing between groups to eliminate the possibility of phase-to-phase short-circuits.

One of the unit trucks is shown in Fig. 2. The upper section of the housing contains the buses and disconnecting switches. The 12 000 volt oil circuit-breakers are mounted on wheels and housed in the lower half. The entire equipment is remotely controlled, the oil circuit breakers operated by solenoids and the disconnecting switches operated by motors. The actuating mechanisms are placed in the other side of the steel cells.

The operating levers for the three phases of each feeder run behind the cells. Each truck may be run from its housing onto the platform in front. This provides ample room for inspection and maintenance and also adds to safety in maintaining the equipment.

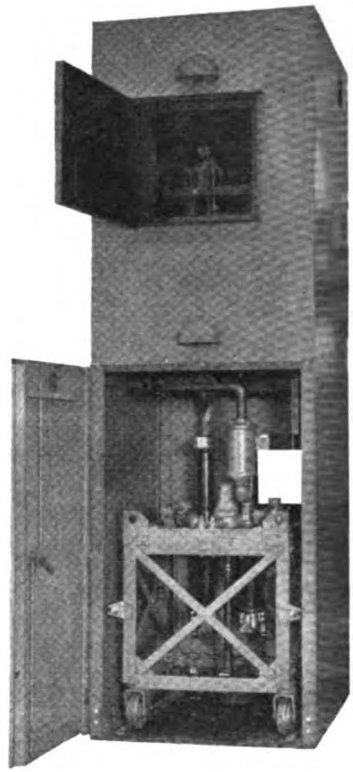

FIG. 2—ONE OF THE UNIT HOUSINGS

# RAILWAY OPERATING DATA

THE ELECTRIC JOURNAL

July 1928

The purpose of this section is to present accepted practical methods used by operating companies throughout the country.

The co-operation of all those interested in operating and maintaining railway equipment is invited. Address R. O. D. Editor

## Inspection and Upkeep of Drum Type Controllers

IN street railway service the drum type of controller, if used within its rated capacity and given systematic care and attention, gives a good account of itself. Sometimes these controllers are subjected to unusually rough treatment in the hands of careless and inexperienced operators, which makes it all the more essential that they be regularly and systematically inspected to keep them in good operating condition.

### INSPECTION

As a result of thirty-eight answers sent in by operators on various size properties in reply to a number of questions in the A.E.R.A. question box on the frequency of inspections on drum controller fingers and segments, the following was obtained:—

1—On a mileage basis, from 500 to 2000 miles, the average being about 1000 miles.

2—On a time basis, from one to seven days, the average being about five days.

3—Operators were about equally divided between the mileage and the time basis for inspection periods.

Inspection on the mileage basis seems to be a more dependable scheme than on the time basis, but this should be decided by each operator, to best fit in with his local maintainance conditions. One large operator who was inspecting his drum controllers on a thousand mile basis found it desirable to shorten their inspection periods to every 500 miles, as they were having too many control failures on the road. In general, this inspection should include the following:—

1—The inside of the controller should be cleaned. One inspector has mounted an outlet connection in the air line near the controller. This is fitted with a short hose and is used to blow out the controller when it is inspected.

2—The drums thoroughly wiped to remove the carbonized and any charred parts on the insulation. Repaint these parts with a good arc-resisting compound.

3—Roughened fingers and segments should be cleaned with a fine smooth file.

4—Badly burned fingers or segments should be replaced by new ones.

5—All fingers must be set square and firm on the segments, allowing about ⅛ in. set or lift on the finger tips.

6—All fingers should set firmly on the segments, especially in the last operating position, as this is the final parallel position all motors must have good connections.

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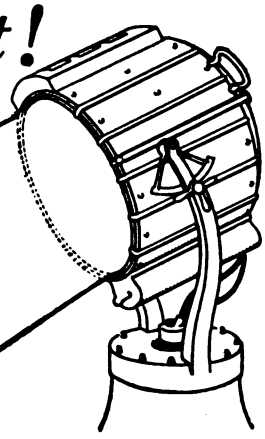
# 2 power plants discover economies

## —*with the same searchlight!*



### In Plant No. 1
### Reliable operation gained
### Oil costs reduced

This Indiana Heat and Light plant operates 3 large plants.

There is a load demand for unit No. 3 (a 4,000-kw. steam turbine) 15 hours per day, 300 days a year. Emulsification of the oil formerly used necessitated frequent shutdowns during periods of load demand. Large amounts of oil had to be thrown away at frequent intervals.

Gargoyle D.T.E. Oil Light was put in service. Suggestions made by the Vacuum Oil Company on correct oil handling were adopted.

"Out of service—charge to lubrication" is no longer entered against the unit. Load is carried as demanded. In addition there is a remarkable reduction in oil cost.

Consequently, this operator now uses nothing but Gargoyle D.T.E. Oils in all units and auxiliary equipment.

Almost every turbine operator "swears by" Gargoyle D.T.E. Oils.

There is a good reason for this. The value of Gargoyle D.T.E. Oils is properly measured in:

1. Maximum reliability of service.
2. Lowest actual oil costs.

### In Plant No. 2
### Oil cost reduced to $.0037 per 1000-kw. hours

This large Street Railway power plant operates a 20,000-kw. turbine.

Prior to 1922 oil costs had been high.

A change in lubrication was made.

Four years and three months after Gargoyle D.T.E. Oil Light had been installed the following service and cost records were made:

| | |
|---|---|
| Total turbine hours operated | 23,811 |
| Total kw. hours | 317,318,651 |
| Lubricating cost per turbine hour | $.0491 |
| Lubricating costs per thousand kw. hours | $.0037 |

This was a considerable saving over their previous costs.

TURN the searchlight of inquiry into your lubrication problem.

Economies are sure to show up somewhere. Perhaps you will only economize on your oil consumption.

Perhaps hundreds—even thousands—of dollars can be saved in power, maintenance, depreciation and labor.

The successful experience of the Vacuum Oil Company in helping power plants to economize by correctly applying the correct grade of oil in the correct amount, may be of help to you.

NOTE: On request we will send you, without obligation, our authoritative treatises: "Steam Turbine Lubrication," "Hydraulic Turbine Lubrication." Write for your copies.

# Vacuum Oil Company

*Headquarters:* 61 BROADWAY, NEW YORK

*Branches and distributing warehouses throughout the country*

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**Lubricating Oils**

The world's quality oils for plant lubrication



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7—The reverse drum fingers should have secure contact on each set of segments.

8—Examine carefully all wire leads, noting if they are scorched or loose.

9—The control should be lubricated as outlined in the following paragraph.

LUBRICATION

The top and bottom bearings on the main and the reverse drums, also the star wheel on the main drum should be oiled only about every 30 days or every fifth regular inspection period. On the other hand, the segments on the main and the reverse drum should be lubricated at every inspection by

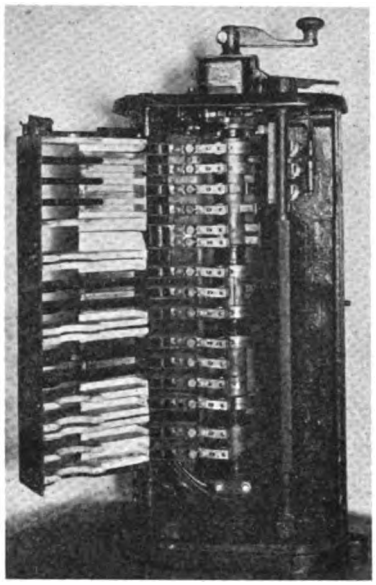

FIG. 1—THE INTERIOR OF A DRUM TYPE CONTROLLER
Showing the new compensating finger in place.

spreading the lubricant, preferably a light oil, over the segments in a thin layer. Operate the fingers over the segments several times and then wipe around the fingers and sides of the segments to remove all surplus lubricant. Excess lubricant is of no value and is objectionable as it is soon wiped or burned off and collects on the arc barriers, fingers and drums, causing carbonizing. Further, it collects copper dust and dirt which is liable to cause insulation failures. Too much lubricant tends to make the segments sticky and dirty. Vaseline is objectionable as it is difficult to apply under all conditions, in a thin film.

MAINTENANCE AND UPKEEP POINTERS

In connection with the repair and general over-hauling of the drum type controllers, the following should be given some consideration:

1—Clean the inside of the controllers by means of a sand blast.

2—Make a suitable jig to assemble the cylinders on the shaft.

3—Preferably use the hexagonal shaft instead of the old, round type.

4—Use the latest type of spacing collars, made from a better arc resisting material.

5—In building up the cylinders do not neglect to use the heavy felt washers between the spacing collars and the cylinder castings.

6—See that the finger shields with the supporting blocks where used, are in place to insulate the finger adjusting support from the segments on the main drum.

7—Clean the segments and the contact tips on the fingers on both the main and reverse drum and finger-boards.

8—Fingers should be adjusted so that the tips make a good contact on the segments. Check these contacts with an 0.002 inch feeler gauge.

9—Finger pressures for the old type of fingers should be as follows:

| Contact Tip, Width | Pressure |
|---|---|
| 1 inch | 8 lbs. |
| ¾ inch | 6 lbs. |
| ½ inch | 4 lbs. |
| ¼ inch | 2 lbs. |

With the new, compensating type of finger the pressures should be maintained at approximately 60 percent of these values.

10—All fingers should be set for about ⅛ inch lift. This should be checked in all positions of the drum. This is quite necessary on account of eccentric drums, or worn bearings and shafts.

11—Keep all screws tight in the terminals on the connection board and blow out coils. See that check nuts with lock washers are used on these screws.

12—Adjust the jaws of the motor cut-out switches so that switch blades make a good contact when thrown into position.

13—Do not use any paint, varnish or compound on the arcing plates.

14—Paint the insulating parts on the inside of the controller with a good grade or shellac or special insulating compound.

15—Wrapping friction tape over the insulating spacing collars an the cylinder is objectionable.

16—On all metal parts subjected to flashing, provide added insulation in the form of sheet asbestos or red fibre.

TABLE I—LIFE OF DRUM CONTROLLER PARTS

| | Miles | | |
|---|---|---|---|
| | Minimum | Maximum | Averag |
| Contact Tips | | | |
| Without line switch | 3 000 | 75 000 | 35 000 |
| With line switch | 12 000 | 120 000 | 50 000 |
| Segments | | | |
| Without line switch | 2 000 | 350 000 | 53 000 |
| With line switch | 8 000 | 350 000 | 103 000 |

17—All exposed metal parts of magnet or frame should be covered with a heavy insulating paint or compound.

18—Wood covers, asbestos lined are preferable to the old iron covers.

19—Test all repaired controllers for 2 000 volts to ground.

AVERAGE LIFE OF TIPS AND SEGMENTS

A summary of the answers received to the questionnaire in the A.E.R.A. gives the information in Table I as to the life of contact tips and segments on the drum type of controllers.

In general, operators are of the opinion that where line switches are used in connection with their drum controllers the life of the contacts and segments are increased from 2½ to 3 times. These figures cover both the old type bronze fingers and the new type compensating fingers. The respective results cannot be segregated.

SELF-ALIGNING COMPENSATING FINGER

The self-aligning, compensating type of finger was developed to meet the demands of some of the larger railway operators for an improved finger mechanism. The features of this new design consist mainly in a spring movement obtained by the action of a steel wire helical spring, between

FIG. 2—THE NEW COMPENSATING FINGER FOR VARIOUS TYPES OF DRUM CONTROLLERS

two steel members. One of these members is used for mounting the finger while the other carries the heavy copper contact tip. A rolling action is provided between the two steel members which permits the contact tip to find its own seat on the segment. Some of the outstanding features of this type of finger are:

1—Sturdy construction, which minimizes breakage.

2—Self-aligning, which insures a good contact on irregular drum segments, with a reduced pressure.

3—Reduced pressure, which increases the life of both the finger tips and the segments.

4—The pressure spring does not carry any current, which insures a uniform spring pressure during the life of the fingers. It also minimizes the burning of the fingers on short circuits and overloads.

JOHN S. DEAN.

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# The JOURNAL QUESTION BOX

Our subscribers are invited to use this department as a means of securing authentic information on electrical and mechanical subjects. Questions concerning general engineering theory or practice and questions regarding apparatus or materials desired for particular needs will be answered. Specific data regarding design or redesign of individual pieces of apparatus cannot be supplied through this department.

To receive prompt attention a self-addressed, stamped envelop should accompany each query. All data necessary for a complete understanding of the problem should be furnished. A personal reply is mailed to each questioner as soon as the necessary information is available; however, as each question is answered by an expert and checked by at least two others, a reasonable length of time should be allowed before expecting a reply.

2838—CORRECTION OF RATIO ERROR—Please advise how to use the correction for ratio error in conjunction with watthour meters. Taking the following case: current transformers at 50 percent load, true ratio 119.3, marked ratio, 120, correction factor 0.994; voltage transformers marked ratio 20:1, true ratio 19.86:1, correction factor 0.993, combined ratio correction of voltage and current transformers 0.993 × 0.994 or 98.7 percent. If the watthour meter at 50 percent load has an efficiency 100.6 percent would the adjustment for the watthour meter be as follows, 100.6 × 98.7 or 100.6 percent +1.3 percent = 101.9 final eff. If the ratio correction was 100.6 percent and the watthour meter 100.6 percent, the final eff. 100.6 — 0.6 = 100.0 percent. That is, when the ratio correction is greater than 100 percent you subtract and less than 100 percent you add for the final efficiency. If we take 100.6 × 100.6 it equals 101.2.

L. C. H. (NEW YORK)

The correction factor is defined as that factor by which the registration of a meter unadjusted for ratio or phase angle error of an instrument transformer or transformers must be multiplied to obtain the correct registration. It is also the accuracy of a meter properly calibrated for ratio or phase angle error of the transformers when the meter is tested alone, in order to be correct when used with transformers. See N. E. L. A. Metermen's Handbook, p. 1011. The correction factor 98.7 percent means that the ratio errors of the instrument transformers cause the meter to register 1.3 percent fast. As the meter without transformers is 0.6 percent fast, the total error would be 1.9 percent fast. The total factor which would take care of the transformer ratio errors and the meter error would be 98.1 percent. For example, if the kilowatt-hours registered by the meter were 950, then the true kilowatt-hours would be 98.1 percent of 950 or 932. If the meter is to register correctly, it should be calibrated to run 1.3 percent slow when tested independently of the transformers. If the correction factor is 100.6 percent and the meter is 0.6 percent fast, as in the previous case, then the errors would cancel and the registration would be correct. C. O.

2839—TRANSFORMERS IN PARALLEL—Referring to Fig. (a), will the two three-phase transformers operate satisfactorily in parallel. The transformers are of the same make, kv-a capacity, voltage rating, polarity, regulation, etc. The internal connections are star on the high-tension, or primary side, and delta on the low-tension, or secondary side. Due to the physical layout of the high tension buses it is desired to let the primary connections remain as shown. J. R. L. (PENNA.)

Assume that the two transformers are identical as to polarity in which case vector conditions are represented by diagram Fig. (b). Now in making the connection on the primary side indicated in the question the leads are connected,—*H-3 to H-1, H-2 to H-2, H-1 to H-3.* The vector diagram should be drawn as follows:—For the transformer on the left, the diagram remains as before but for the transformer on the right, the diagram must show its primary phase rotation reversed. The primary diagram for this unit now becomes as shown in Fig. (c). The question now is, what is the relative phase position of the two secondary delta voltages? The diagram for the transformer on the left remains the same as before. The delta voltage

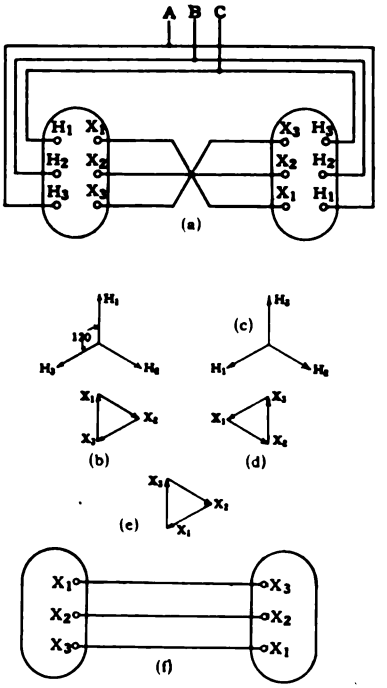


FIG. 2839 (a), (b), (c), (d), (e) and (f)

for the transformer on the right is shown in Fig. (d). This is drawn by making *X-1* parallel to *H-1* in Fig. (b), *X-2* parallel to *H-2* and *X-3* parallel to *H-3*. Will the two deltas in Figs. (b) and (d) now parallel? Evidently not for, if *X-1* and *X-3* are connected and *X-3* with *X-2*, the points *X-2* and *X-1* are not at the same potential. Paralleling conditions may now be established by interchanging windings, *X-1* and *X-2* as they are connected in the secondary delta of the second transformer. This delta then becomes as shown in Fig. (e) and parallel operation is secured by connecting *X-1* to *X-3*, *X-2* to *X-2* and *X-3* to *X-1*. The actual secondary connections are shown in Fig. (f) with the primary connections the same as in Fig. (a). This is a commonly misunderstood connection and due possibly to the fact we pay too much attention to the external leads instead of the internal connections. As a matter of fact it makes no difference to a pair of transformers whether they are connected symmetrically or back-to-back. E. G. R.

2840—TESTS OF CURRENT TRANSFORMERS—What tests could be made on bushing-type current transformers to determine ratio and polarity and which test is best? I refer to transformers used on outdoor oil switches for relay operation, etc.

R. A. B. (MASS.)

The exact current ratio as well as the phase angle are important for transformers used for power measurements. The usual method of determining the current ratio is by the use of ammeters. One meter is connected in the primary circuit and one in the secondary. The meters should be selected to work on a favorable part of the scale. The polarity marking of current trans-

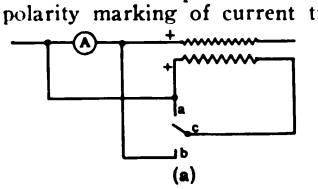


FIG. 2840

formers may be checked as follows:—(a) check against a standard transformer with a wattmeter. Connect a standard current transformer to a wattmeter or watthour meter whose potential coil is suitably excited. Note the direction of deflection. Disconnect the standard transformer and connect the transformer to be tested. The marked leads should be connected in the same way as those of the standard transformer. If the wattmeter deflection is in the same direction as before, the polarity of the two transormers is the same. (b) Check with an ammeter. Connect an ammeter in the marked primary lead, and connect the secondary as shown in Fig. (a). With secondary lead *c* connected to *a*, put a known current through the primary winding and read the ammeter. Then connect the unmarked secondary lead to *b*, put the same current through the primary, and read the ammeter again. If the second reading is larger than the first, the markings are correct. In making either of these tests care should be taken not to open the secondary circuit while current is flowing in the primary.

E. G. R.

2841—FAILURE OF SINGLE-PHASE MOTOR TO START—I would like an explanation of the following experience with a single-phase, 110 volt motor. At times it would not start but

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would only hum which would indicate an opening in one of the two windings. Then again, it would run all right. This I put down to a loose or dirty connection on the centrifugal switch in the starting winding. A single-phase motor with one winding open will run in either direction, depending on which direction the effort is applied. This motor in question was placed on a bench and when the power was turned on it would pick up at times and run. Then again it would just hum. Then suddenly start to run but in the opposite direction to what it did before. I turned off the power, let the motor come to rest, turned the power on again and it started up, but in the opposite direction. The rotor turned freely by hand, didn't stick in any position. When this motor would hum and not pick up immediately was there sufficient vibration due to the humming to cause the motor to act as stated above?

J. E. W. (CANADA)

A single-phase motor if the slot combination is suitable, will often start at no load by a very slight impulse applied to the rotor. Also in a squirrel-cage rotor, the resistance of the various paths composed of rotor conductors and resistance rings, may vary slightly due to the contact drop between the bar or rotor conductors and the resistance ring. At standstill with voltage on the single-phase primary, the rotor would normally tend to turn so that the low resistance path would span the full pole set up by the primary winding. This impulse would be in the direction of the nearest pole. In one case the impulse might be in one direction and the next time in the opposite direction. This impulse may be of sufficient amount to give the rotor the necessary start which would carry on beyond the position the low resistance circuit would normally take under the field at standstill, the motor coming on up to speed. This initial impulse under the locked condition might possibly result from some other cause such as a difference in the reluctance of the magnetic circuit for one position of the rotor with respect to the stator core. In case of a variable reluctance, the rotor would tend to take up a position where the lowest reluctance circuit would be in the center of the nearest pole and this turning effect might be sufficient to get the motor started to come up to speed at no load. We believe the trouble with the motor in question is an open circuit in the starting winding or as you suggested, dirty or a loose connection between the starting winding and the starting switch.

M. W. B.

2842—Overcurrent Relays—1—What effect has the wave shape of the current upon the time of closing of a type *CO* overcurrent relay? 2—Would you suggest a method for field testing of relays whereby sine wave current is produced?

B. V. V. (OHIO)

1—A distorted wave shape of current causes the relay to take a longer time to operate than with a sine wave of current. The relay will require from 0.1 to 0.2 of a second longer to trip when tested on a phantom circuit or any circuit where a distorted current wave exists. 2—A distorted wave shape of current usually arises from the presence of an iron core reactor in the circuit, such as the electromagnet of the relay itself. If the reactor is the predominating part of the impedance of the circuit, the wave shape of current becomes distorted due to the hysteresis loss in the iron. If the impedance of the circuit is made largely resistance, the wave shape of current resembles the applied source of voltage in form, which we assume is a sine wave. Type *CO* overcurrent relays should be tested on a 110 or 220 volt source with the current through the relay limited by series resistance. Such a method of testing closely resembles actual service conditions.

R. M. S.

2843—Calculation of Transformer Impedance—Three single-phase transformers are connected as shown in Figs. (a) and (b). It is required to obtain the impedances between the circuits as designated. Are the following values correctly derived?

$$Z_{ab} = \frac{E'_0}{E} \times 100, \text{ percent}$$

$$Z_{ac} = \frac{E_0'''}{E} \times 100, \text{ percent}$$

$$Z_{bc} = \frac{E_0'''}{E} \times 100, \text{ percent}$$

$$I = \frac{3 \times \text{kv-a}}{1.73\,E}$$

$$I_1 = \frac{3 \times \text{kv-a}}{1.73\,E_1}$$

where kv-a is the rating of one transformer. Then, $Z_{AB} = Z_{ab}$ percent, $Z_{AC} = Z_{ac}$, and $Z_{BC} = Z_b + Z_c = Z_{bc}$ percent. S. C. (CANADA)

The method of determining impedances between windings in pairs is correct except that the impedance should be based on current values in the short circuited winding rather than in the primary winding. This is important in a three-winding transformer since the various windings may all have different kv-a rating. The relative ratings in the various windings depends upon whether the two secondaries can be loaded simultaneously at their full or partial rating. The final expression obtained of the impedance between systems is correct only if the third winding is idle. A simple method of representing such a transformer has been developed by substituting a star connected net-work to represent the equivalent impedances between windings. This is discussed and the formulae given in the N. E. L. A. Relay Handbook p. 930. From this it will be seen that it is not possible to add directly the impedances of the two windings due to the mutual effect on these of the third winding. The term three-winding transformer used above is used in its broad sense as indicating three simultaneous voltage supplies. The fact that two windings are interconnected as an autotransformer does not affect the results or use of the three-winding formulae except as impedances are modified by the autotransformer connection as compared with separate windings.

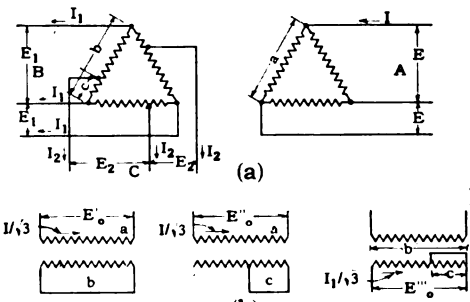


FIG. 2843 (a) and (b)

W. R. W.

2844—Peculiar Behavior of Ground Detector—My attention was lately called to the peculiar action of an electrostatic, three-phase ground detector (with three single-phase elements) on the switchboard of the local power plant. A ground was registered on one phase of this instrument, which hand remained stationary. On the other two phases the hands oscillated from side to side, beginning with a short movement which gradually increased to almost the full length of the scale, and then died down gradually almost to a stop, when the same cycle would be repeated. During this cycle, the hand on the grounded phase at first remained stationary, but several times showed a tendency to swing with the others, but as far as I could see the movement was slight and died down after two or three attempts. The movement of the ungrounded phases at first synchronized, but got out of step at a certain length of swing, and was irregular for a period, when they would again be in step, remaining so for possibly a minute. The movement of the hands was about 50 or 60 to the minute. The oil switches were opened one after the other to locate the ground, and also to see if there was a possibility of more than one, but the oscillations continued. Lowering the frequency to 59.5 cycles steadied the instrument for a short period, when it again started. The movement was continuous until the plant was tied in with the high-tension system (132 kv) when the oscillations ceased. The power plant generates at 6600 volts, three-phase, 60 cycles, and was operating two 1000 kv-a steam turbogenerators with a load of about 6000 kv-a. The recording instruments showed the voltage, frequency, and load to be steady. This instrument has been in service for about eight years, and while grounds on the system have been indicated at various times, this is the first time that it has acted in this manner. I will appreciate an explanation of the above, and why the movement ceased when the plant was synchronized with the high-tension power line.

F. W. (TENN.)

The peculiar behaviour mentioned is probably due to the presence of beats between the frequency of the 132 kv line voltage and the 6600 volt line due probably to some sort of coupling between the meter and both lines. It may be due to variations in ground voltage caused by a high resistance ground common to both lines. This theory can be checked by plugging in the synchroscope and observing if the swinging is the same frequency as rotation of the synchroscope. How the high voltage affects the meter will have to be located locally if above test proves the theory.

B. E. L.

## CORRECTION

The first two lines of the last paragraph on page 294 in the Journal for June 1928 should read: "Where it is desirable to over-insulate the line to prevent outages, normal insulation should be used" etc.

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# THE ELECTRIC JOURNAL

VOL. XXV AUGUST, 1928 NO. 8

**The Mathematics of the Amoeba**

The amoeba is a curious animal. Too small to be seen without a high-powered microscope, he makes the most of his opportunities. Without mouth, he eats. Without muscles, brain, nervous system or sense organs, he travels in the direction of food. He could hardly understand mathematics; yet he has learned to overcome the limitations imposed by certain laws of geometry—namely, the surface area of a solid increases with the square of the linear dimensions, but the volume increases with the cube. When the amoeba grows, soon his outside can no longer provide for his inside. Euclid himself could not have solved the problem more neatly. The amoeba bisects himself. The two amoeba now again comply with the inexorable law.

The totally enclosed industrial motor has been limited by the same mathematical principle as the amoeba. It functions admirably when small—not over five to ten horse-power at ordinary speeds. Increase in rating*, with the same limit of internal temperature, means a disproportionate increase in size, weight and cost. Finally at a certain size and speed, without a freak design at prohibitive expense, the motor will overheat at zero load. It is in a sad fix. Its outside is not big enough for its inside. Fission, which solves the amoeba's problem, is not so good for the motor.

There was, however, in the early days, a cousin of the amoeba who found that, while fission was necessary, there were advantages in having the two resultant cells stick together, to help one another in the strenuous business of life. Some designer seems to have harked back way beyond the proverbial monkey to this more remote ancestor; for he has in the same way overcome the mathematical limits of the enclosed motor, which now becomes two co-operative units. One does all the work for the pair; and in doing so releases heat. The other devotes its entire resources, received from its fellow, toward keeping its fellow in working condition—a very nice, family sort of arrangement, the practical workings of which are described by Mr. Nelson in this issue of the JOURNAL.

This division of functions is especially desirable for squirrel-cage motors, whose rotors are highly heat resistant. With wound-rotor motors, especially in the smaller sizes, the approach to open motor characteristics is not quite so close. The method is possible with direct current, but is not so widely applicable as with the induction motors, because cooling is practicable from one end only.

*See "Characteristics of Direct-Current Motors", by R. W. Owens, in the JOURNAL for Jan. 1926, p. 37.

It has, of course, always been possible to ventilate an enclosed motor by a separate motor-driven blower and ducts, drawing the air from a clean source. This system has, however, been too expensive for the smaller motors. The great advantage of the new fan-cooled motor is that it closes the gap in lines of enclosed motors between the self-ventilated and the separately ventilated motor. Motors of the enclosed, fan-cooled type have been built up to 150 hp at 720 r.p.m.: and there seems to be no reason to believe that this is the upper limit. Their performance and, in fact, size and general appearance, are not greatly different from the ordinary open motor.

CHAS. R. RIKER

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**The Increasing Importance of Craftsmanship**

The craftsman is an important member in any large manufacturing organization. There is a prevalent idea that craftsmanship is disappearing. Not so, say the leaders in industry. At no time have there been better opportunities, or greater demand than now; his value to industry is constantly growing.

It is true that the activities of the present-day craftsman have changed from the actual making of intricate mechanisms to the making of tools so that a less skilled man can do the work better and faster. But in this change he has multiplied his usefulness a thousand fold.

Those who have seen the complicated and ingenious automatic machines that perform nearly all of the intricate operations of making incandescent lamps have marvelled at the constructive ability of those who made them. They are due to the skilled mechanics who contrive and build them. A prominent man in the lamp industry is authority for the statement that the incandescent lamp as now made would not be possible without these men.

Another instance of the multiplication of his efforts is the case where a die was required for accurately punching in a disc a great number of square holes eight thousandths of an inch on a side. The skill of a toolmaker produced it.

One of the problems of industry is to find the potential ability, and to develop the craftsmen it requires. Furthermore, it requires time for the learner to acquire the requisite skill of mind and hand.

To those who are now the craftsmen of an organization comes the allurements of constantly changing work and new, interesting problems. To those who are not comes the appeal to train themselves in craftsmanship through the means now so extensively available.

W. A. DICK

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# Relative Frequency of Voltage Surges Induced by Charged Clouds

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Electrical Engineer,
The Cleveland Electric Illuminating Co.

THE behavior of thunder storms, as regards surge voltages induced in transmission lines, is very erratic. No two seasons and seldom two storms produce directly comparable results in the matter of the severity of induced voltage surges or of the flashovers resulting therefrom. The condition of the insulators, whether wet or dry, clean or dirty, also modifies the flashover voltage and therefore, of two circuits on a pole line, one may be tripped due to an insulator flashover while the other circuit will remain unaffected. A charged cloud may be partially discharged by a lightning stroke before passing over a line and the resulting bound charge imparted to the line, therefore, may be relatively small; or the cloud may pass, without previous discharge, over the line and either discharge directly to it, or induce on it a heavy charge to be released after the cloud has discharged to earth

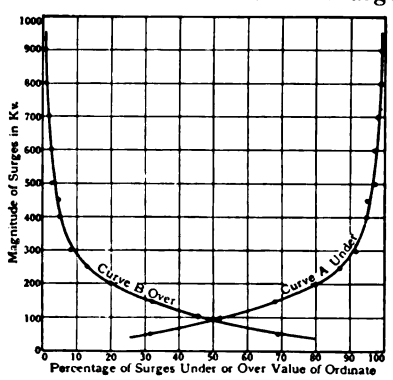


FIG. I—PERCENTAGE OF SURGES ABOVE OR BELOW ANY CERTAIN VOLTAGE

while still in the immediate vicinity, with a resulting high potential induced in the line conductors.

No means are available to make direct comparisons of thunder storm intensity. Therefore, any estimate of the value of remedial measures that might be put into effect to reduce outages on transmission circuits, must always be qualified with the proviso, that for a storm of given intensity the amelioration to be expected would be of the order of.....,etc.

It has long been known in theory that overhead ground wires installed on transmission lines will exercise a shielding effect, whereby the surge potential induced in a line by a cloud will always be less than that induced in an unshielded line. The shielding effect will vary with the number and positions of the ground wires installed, and their ability to influence the induced charges will depend somewhat upon the material used for the ground wire, the frequency of its earth connections and their resistances. The percentage of shielding effect can be closely calculated and numerous values for different combinations have been published.

For a time, at least, the use of overhead ground wires fell more or less into disrepute, principally because of mechanical failures resulting from the use of improper materials and poor methods of attachment. Present practice indicates a trend toward the resumption of their use with improved installation methods: and all comparable operating data indicate improvement in line reliability, usually marked, when overhead ground wires are properly installed.

While in the past it has been possible to predict the percentage of reduction in the voltage of induced surges which would result from the installation of ground wires, there was no means of predicting what might be the reduction to be expected from such an installation in the number of induced surges of a magnitude equal to or greater than the flashover voltage of the line insulation.

Data now available make this possible. Fig. 1, curve $A$* has for ordinates surge voltage in kilovolts and for abscissae the percentage of surges not exceeding the value of a given ordinate. Curve $B$ is plotted to the same ordinate to show the relation between induced voltages and the number of surges which exceed a given ordinate. Curve $A$ was plotted from data taken from almost nine hundred Klydonograph records and the relative frequency of surges shown thereby may, therefore, be accepted as reasonably reliable. Fig. 2 represents curve $B$ when plotted to logarithmic coordinates, the straight line having the equation

$$\log y = \log 895 - 0.5 \log x$$

and the points plotted show close agreement with this line. From Fig. 2, or from the equation, it will be seen that for any chosen value of $y$ with its corresponding value of $x$, the value of the abscissa corresponding to $y/2$ is $4x$, to $y/4$ is $16x$, or more generally to $y/n$ is $n^2x$.

Here then we have a law for the relative probability of occurrence (frequency) of induced surges of a given magnitude (and over), which may be stated as follows: If the relative frequency of induced voltage surges of a given magnitude (and over) be chosen as unity, the probabilities are that $n^2$ times as many surges of $1/n$ times the above magnitude (and over) will be induced in a given conductor by the electrostatic action of charged clouds.

The maximum value of the electrostatic potential

*Reproduced from the paper by Cox, McAuley and Huggins on "Klydonograph Surge Investigations" presented before the A.I.E.E. in February 1927.

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gradient due to charged clouds has been generally accepted as 100 kv per foot as set by Peek. If then we consider a conductor $H$ feet above earth, the maximum voltage induced in it will accordingly be 100 $H$ kilovolts. If we assume the relative frequency of this magnitude of induced voltage to be unity, we may expect a probability of four surges of not less than $50H$ kilovolts, of one-hundred surges of not less than

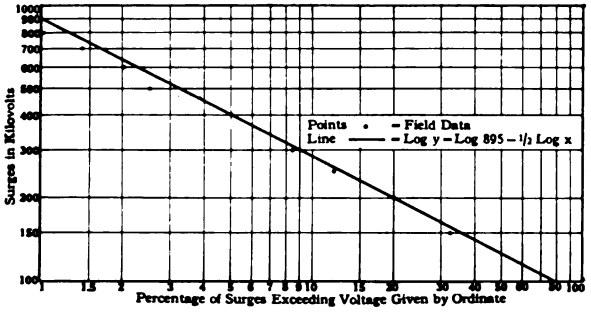
Surges in Kilovolts
Points • = Field Data
Line —— = Log y = Log 895 − 1/2 Log x
Percentage of Surges Exceeding Voltage Given by Ordinate

FIG. 2—ACTUAL AND CALCULATED VALUES OF SURGES EXCEEDING ANY CERTAIN VOLTAGE

$10H$ kilovolts, etc. Practical use may be made of this relation.

*a—Effect of Varying the Height of the Line Conductors as Affecting Probable Outage Ratio*—It is desired to compare the relative reliabilities of two 132 kv lines, each insulated with strings having a crest flashover voltage of 1000 kv. One design calls for a double-circuit tower with vertical arrangement of line conductors, the top conductor being 80 feet above earth. A second design is based on single circuit towers with horizontal arrangement of line conductors, 55 feet above earth.

From Fig. 3 it is seen that the relative frequency of induced surges of 1000 kv and over is 64, if the frequency of maximum surge, 8000 kv, is taken as unity. For the 55 foot line, however, the relative frequency of surges in excess of 1000 kv is shown to be 30 under similar assumptions. From these figures the expectancy of reliability, as affected by lightning, is 2.1 times as great for the low line.

*b—Effect of Varying the Flashover Voltage of the Line Insulation as Affecting Probable Outage Ratio*—Consider a line for which two insulator strings are being proposed, one of eight units with 695 kv crest flashover voltage, and one of ten units with 840 kv crest flashover voltage. Let the conductor height be 60 feet. The relative frequency of induced surges of flashover value or greater, from Fig. 3, is as 75 to 51 for the two cases. The expectancy of reliability is 1.47 times as great for the line insulated with a ten unit string. Or from another point of view, the addition of two insulators to the strings, and the consequent heightening of the towers by about one foot, yields results comparable with those to be expected from a line with conductors 49 feet above earth and insulated with eight unit strings.

*c—Effect of Installing an Overhead Ground Wire on Outage Ratio*—Assume the 60 foot conductor height line with 8 unit strings of insulators previously discussed. Let ground wires be located on the towers so as to produce a shielding effect of 40 percent. The maximum induced voltage will be reduced from 6000 to 3600 kv, and the relative frequency of surges equal to or greater than 695 kv will be 26 as against 75 without it. The expectancy of reliability for the shielded line is 2.9 times as large as for the unshielded line.

*d—Effect of Insulating an Overhead Ground Wire from the Structures on Wood Pole Lines*—Assume that a wood pole transmission line is to be built with top conductors 38 feet above earth, and that a ground wire having a shielding effect of 40 percent is to be installed. What additional reliability may be expected if this ground wire and its earthing connections be insulated from the poles with an insulator having a flashover value of approximately one-half that of the line insulators, all pins and other crossarm hardware being bonded at the pole top?

Assume that the line insulators have a flashover value of 145 kv and the one proposed for the ground wire insulation has a flashover value of 85 kv, the crest values being 210 and 120 kv respectively. The maximum induced potential in the shielded line will be 2300 kv.

Without insulation on the ground wire, surge voltages of 210 kv and over will cause flashover; but

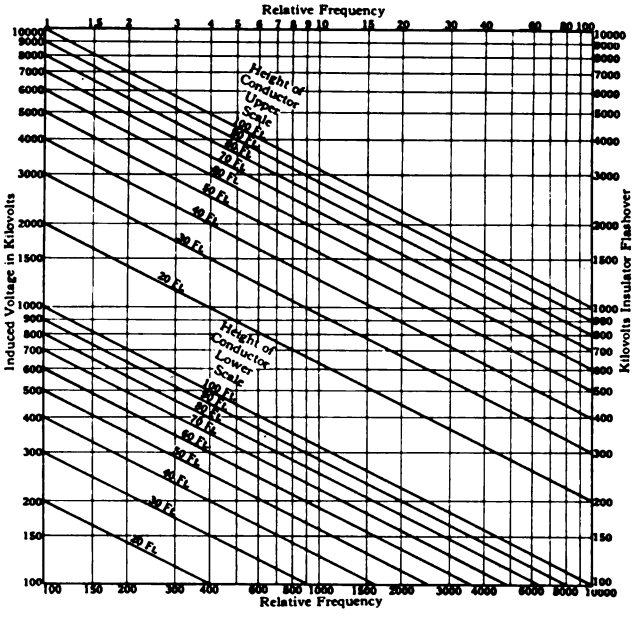


FIG. 3—RELATIVE FREQUENCY OF INDUCED VOLTAGES ABOVE FLASHOVER VOLTAGE

with ground wire insulation 330 kv will be required. The relative frequency of surges of flashover voltage is:—

For the line without ground wire .....328
For the line with uninsulated ground wire .....120
For the line with insulated ground wire ..... 49

and the expectancy of reliability is 2.7 times as great for the line with uninsulated ground wire as for the unshielded line, 2.5 times as great for the line with insulated ground wire as for the line with uninsulated

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ground wire, giving 6.7 times the reliability for the line with insulated ground wire in comparison with the unshielded line.

The lines on the chart in Fig. 3 have been marked in feet corresponding to the height of the top wire. They are also to be considered as voltage lines corresponding to maximum induced kilovolts one hundred times greater. Assume that in the case of example *a* there were data to show that thunder storms were mild in the region considered and that the maximum static voltage gradient would never exceed 50 kv per ft. For the 80 ft. line the maximum induced voltage becomes 4000 kv and the 40 ft. or 4000 kv line is used. For the 55 ft. line, a 2750 kv line is used. These two lines intersect the 1000 kv insulator flashover line at 16 and 7.6 respectively, giving a ratio of 2.1 as the expectancy of reliability for the lower line. It is thus seen that the expectancy remains unchanged, although the relative frequencies used to determine the expectancy differ widely. Hence it is convenient to adopt a frequency of unity for an induced voltage of 100 H kilovolts.

One cannot assume that the outages will coincide with expectancy. Suppose a line had been subject to a great many outages due to lightning, say 50 in one season; and that remedial measures planned and installed prior to the next season indicated that the reliability should be increased five-fold. In the following season the line might trip out due to lightning 2, 10 or 25 times. The lower figure would indicate fewer or less severe storms or both; the higher just the reverse; while the intermediate figure would tend to indicate a lightning season of a severity equal to that of the previous year. But the fact would remain that without such remedial measures as were installed the probable number of outages due to lightning would have been 10, 50 or 125, dependent upon the meteorological conditions prevailing.

It is believed that the examples cited above are sufficient to show the great value of the work done by the engineers who obtained and plotted the records on which this discussion is based, and of the klydonograph itself, without which it would have been impossible to obtain the data.

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# The Polyphase Induction Generator

D. F. ALEXANDER
Industrial Motor Design Engineer,
Westinghouse Electric & Mfg. Co.

THE polyphase induction motor, simple and reliable, has been used in such great numbers and for such a variety of applications that its performance is well understood. On the other hand, few polyphase induction generators are used, as compared to synchronous generators or induction motors, hence their characteristics are correspondingly less familiar.

The general operating characteristics of the induction generator, such as efficiency, power-factor, overload torque and speed are not greatly different from those of the induction motor. There are, however, important differences between the synchronous and the induction generator which require careful consideration if the latter is to be successfully applied. The synchronous generator, excited from an independent direct-current source, may have its characteristics considerably varied to suit line conditions; the induction generator receives its excitation from the alternating-current circuit to which it furnishes power, and thus is largely dependent upon it.

## OPERATION

If an induction motor, either of the squirrel-cage or wound-rotor type, is driven at speeds above synchronism, the power component of the primary current reverses, and the machine becomes an induction generator feeding energy back into the line. There will be no power supplied to the line until the shaft power-input has exceeded the internal losses of the machine. The slip of the rotor, defined as,—

$$slip = \frac{rotor\ copper\ loss}{power\ transferred\ across\ air\text{-}gap}$$

becomes negative, since the flow of power is now from the rotor to the stator, instead of the reverse. As in the induction motor, below full load and with short-circuited rotor, the slip is approximately proportional to the load.

The performance characteristics of the induction generator depend upon the driving source of power, and upon the circuit to which the machine is connected. Two conditions are possible:—

1—The speed of the prime mover increases with load, the line frequency remaining constant.

2—The speed of the prime mover remains constant, the line frequency decreasing with the load.

The first case represents the most common practice, where the speed of the generator must increase to increase the power output. The induction generator may be connected to a power circuit in parallel with synchronous alternators, furnishing as much load as its driving power permits, and running above synchronous speed as much as is required to utilize the power supplied by its prime mover.

The second case would be found where an induction generator supplies power to a synchronous motor, or other suitable circuit which has no definite frequency. The prime mover may operate at a constant speed, determined by its governor, and the line fre-

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quency will decrease for increased generator outputs. The change of frequency with load will be much the same as the drop in rotor speed with load in an induction motor.

The effect of changing the secondary resistance per phase will be the same as in the induction motor, that is, the slip for a given torque will be increased in proportion to the increase in resistance, with decreased overall efficiency. Advantage may be taken of this to change the induction generator speed regulation curve to suit that of the prime mover.

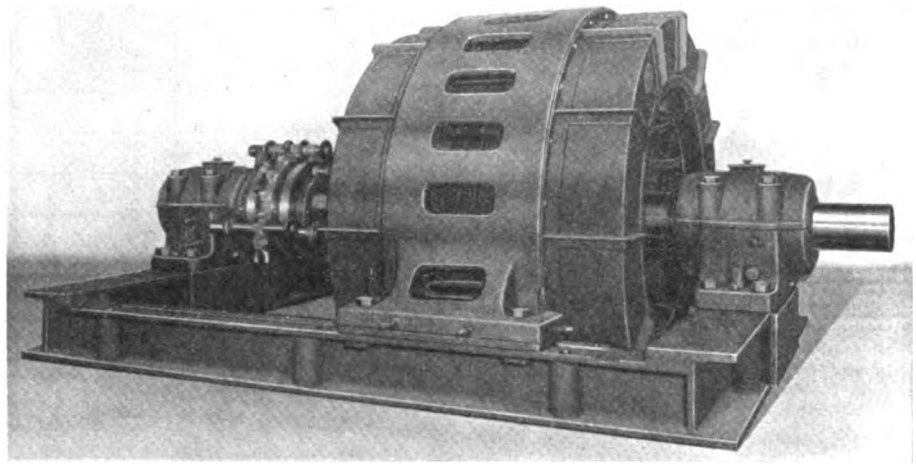

FIG. I—A 1000 KW WOUND-ROTOR INDUCTION GENERATOR

## EXCITATION AND POWER-FACTOR

Although the power component of the line current varies in magnitude and direction during transition from full load as a motor to full load as a generator, the magnetizing component remains practically constant in magnitude and in phase position, as shown in Fig. 2. The induction generator thus requires a source of reactive current for excitation, as does the induction motor. It must, therefore, be connected to some apparatus which furnishes a lagging current, i.e., consumes a leading current, such as an over-excited synchronous motor. In this fact is found the essential difference between the induction generator and the synchronous alternator. The induction generator, for any given load, must operate at a definite power-factor, regardless of the character of the external load. The current must lead the terminal voltage by an angle determined by the voltage and load on the machine. In a synchronous alternator, when it is the sole supply of a system, the phase relation between terminal voltage and output current depends entirely upon the external circuit to which it furnishes power; or, when operating in parallel with other alternators, may be varied by suitable adjustment of the field current to give any desired power-factor. This ability to adjust the power-factor is well known for the synchronous motor, which bears the same relation to the synchronous generator as does the induction motor to the induction generator.

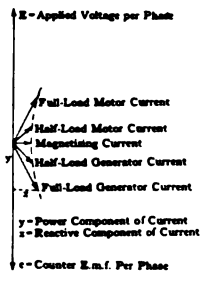
E = Applied Voltage per Phase
Full-Load Motor Current
Half-Load Motor Current
Magnetizing Current
Half-Load Generator Current
Full-Load Generator Current
y = Power Component of Current
x = Reactive Component of Current
e = Counter E.m.f. Per Phase

FIG. 2—INDUCTION MOTOR AND GENERATOR VOLTAGE AND CURRENT VECTORS

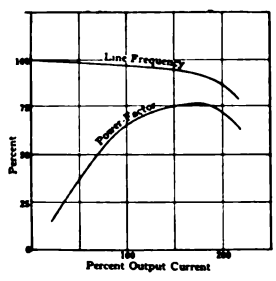


FIG. 3—VARIATION OF POWER-FACTOR AND FREQUENCY WITH LOAD FOR AN INDUCTION GENERATOR, SPEED CONSTANT

The reactive-current component, as shown in Fig. 2, increases with increased load either as a motor or a generator. The power component increases faster than the reactive component, so that the power-factor improves with increased load. However, beyond a certain load, usually beyond rated full load on the machine, the reactive component increases faster than the power component, and the power-factor decreases as shown in Fig. 3. This is similar to the performance of an induction motor.

As previously indicated, the power-factor of an external circuit of impedance $Z$ supplied solely by an induction generator must, at all loads, equal the power-factor of the induction generator for proper operation, drawing a leading current from the generator. If the external load consists of resistance, inductance and capacitance, as shown in Fig. 4, its power-factor is constant and independent of the voltage. The induction generator will not excite until the power-factor of this external circuit becomes lower than that of the generator; when this condition is reached, the latter excites and its voltage rises until, by saturation of the magnetic circuit, the increased magnetizing current has reduced the generator power-factor to equality

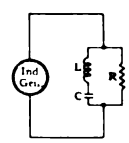


FIG. 4—A CIRCUIT IN WHICH POWER-FACTOR IS INDEPENDENT OF LINE VOLTAGE

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with that of the load. Assuming that the impedance of the circuit could be adjusted so that its power-factor exactly matched that of the generator at all loads of Fig. 3, the circuit voltage would be indefinite, and thus unstable. In this respect, the induction generator resembles the direct-current shunt generator, which becomes stable only at saturation, but loses its excitation and thus drops its load as soon as the voltage falls below saturation. To secure stability, a separately-excited synchronous machine must be connected as part of the load.

The external load may be such that its power-factor depends upon the voltage impressed upon it; for instance, in circuits containing synchronous motors or converters. The synchronous motor in this connection differs from the impedance load of Fig. 4, in that the power-factor may vary with the line voltage, the excitation remaining constant. This is a familiar characteristic of synchronous machines, where the impressed e.m.f. equals the motor counter e.m.f. plus the internal impedance-drop, added in proper vector relation. Reduction in impressed e.m.f. under unity power-factor conditions results in a reduction of power-factor, the current leading the impressed voltage. An increase of impressed e.m.f., on the other hand, results in an increased angle of lag of current with respect to voltage. Similarly, if the line voltage remains constant, adjustment of the field excitation results in change of power-factor. In either case, the voltage of the induction generator connected to a synchronous motor will rise until the motor draws a leading current corresponding to the power-factor demanded by the generator.

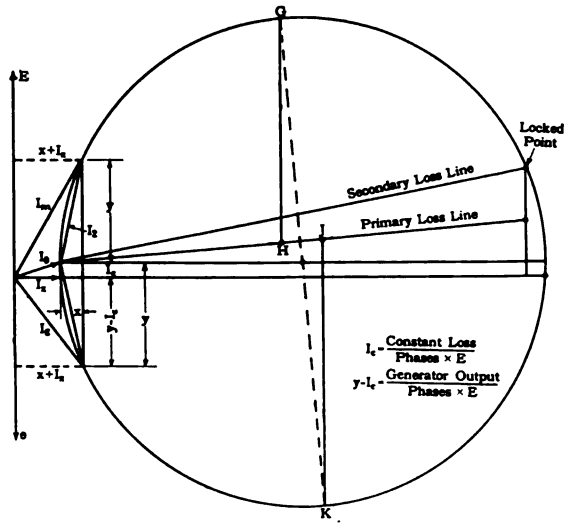


FIG. 5—THE CIRCLE DIAGRAM FOR AN INDUCTION MACHINE OPERATING AS A MOTOR OR GENERATOR

In this circuit, the voltage is stable, and the speed of the motor will be less than that of the prime mover driving the generator by the amount of the slip, increased load resulting in a reduction of line frequency and motor speed. The voltage on the motor also drops, but may be maintained constant, or even increased, by adjustment of the motor field current.

A synchronous motor operating from a constant-speed induction generator will have current and speed-load curves similar to those obtained when operating an induction motor from a synchronous alternator. A magnetizing current flows at no load, with the speed decreasing until the maximum-torque point is reached, when the motor falls out of step and the current rapidly increases. In both cases, the relation of reactive current to voltage is such as to demagnetize the synchronous machine and magnetize the induction machine.

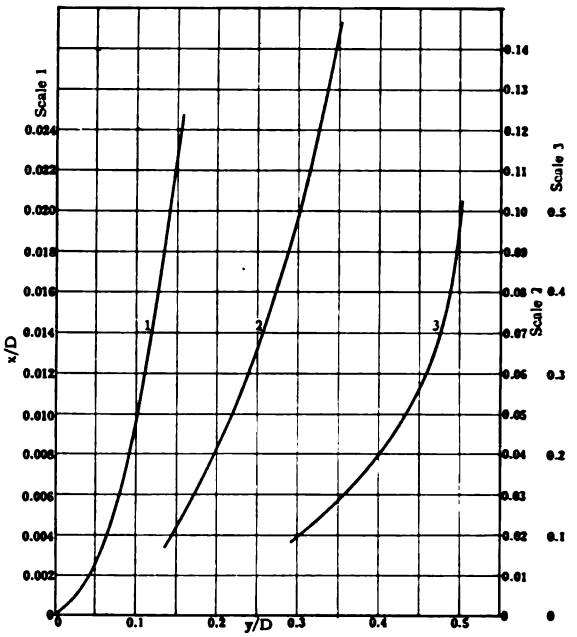


FIG. 6—CURVES SHOWING THE RELATIONS OF $D$, $y$, AND $x$ FOR USE IN CALCULATING INDUCTION MACHINE PERFORMANCE

Should the load be a self-excited synchronous converter, in which the direct-current load counter e.m.f. is not independent of the line voltage, the circuit will be unstable until either generator or converter has reached saturation.

The most common use of the induction generator is on a large system, where voltage and frequency are maintained by large synchronous alternators suitably excited. The exciting current of the induction generator may be derived from synchronous motors on the system, or directly from the alternators. In the latter case, the current may be said to come from the synchronous alternators as lagging currents.

## DETERMINATION OF PERFORMANCE

The performance of the induction motor is usually determined from a circle diagram. From an extension of this method the performance of the induction generator also may be determined. The electrical input and shaft output are negative, that is, the machine absorbs mechanical power and produces electrical power. If the mechanical load upon a motor operating with primary current $I_m$ is reduced, and power is applied to the shaft to drive the machine above synchronism as an induction generator, the primary current vector follows the arc of a circle as its

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locus. This is shown in Fig. 5, which is the familiar circle diagram for the induction machine, with all values reduced to single-phase equivalents.

The various voltage, current, torque and power relations are found in much the same way as for the induction motor. Once understood, it is unnecessary to construct the actual diagram for either motor or generator. All the characteristics may be found by analytical methods.* In Fig. 5, $I_0$ represents the no-

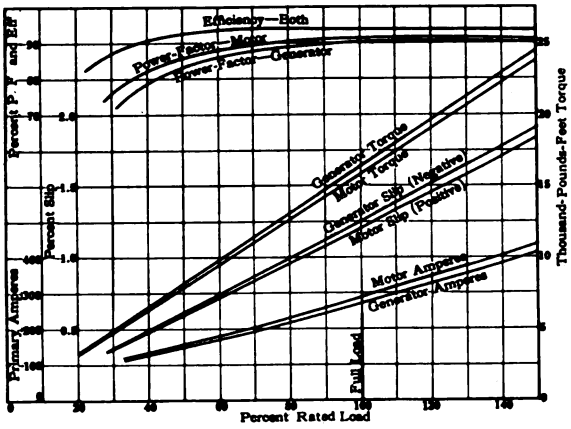


FIG. 7—A COMPARISON OF INDUCTION MACHINE PERFORMANCE AS GENERATOR AND AS A MOTOR, LINE VOLTAGE CONSTANT

load current, to which must be added vectorially the secondary current $I_2$ (expressed in terms of the primary), to obtain the total primary current $I_m$ or $I_g$. $I_0$ remains practically constant for all loads, while $I_2$ and hence $I_g$ vary with the load in such a manner that their vectors move along the arc of a circle, having a diameter,—

$$D = \frac{Primary\ voltage}{Total\ reactance} - I_z$$

If $y$ = power current components and $x$ = reactive current components within the circle as shown in Fig. 5, they are related to the diameter $D$ as follows:—

$$\frac{x}{y} = \frac{y}{D - x} \text{ or, } x = \frac{D \pm \sqrt{D^2 - 4y^2}}{2}$$

The value of $D$ and either $x$ or $y$ being known, the unknown factor may be found easily by a setting of the slide rule and reference to Fig. 6. The method of procedure is first to assume the power component of the line current, $y + I_c$ for the motor, $y - I_c$ for the generator, and then properly combine with $x + I_x$ to obtain the line current. The power-factor $= (y + I_c) / I_m$ for the motor; $(y - I_c) / I_g$ for the generator. Combining $x$ and $y$ gives the secondary current, in terms of the primary.

The currents and winding resistances being known, the primary and secondary copper losses may be found. Adding these to the constant losses and the assumed output, the input, and thence the efficiency, may be found. To find the slip, as a decimal:—

$$Motor\ slip\ (positive) = \frac{W_2}{output + (friction + windage) + W_2}$$

$$Generator\ slip\ (negative) = \frac{W_2}{input - (friction + windage) - W_2}$$

*See the JOURNAL for Dec. 1922, p. 485.

where $W_2$ = secondary copper loss, in watts. Having found the slip, and thus the speed at the assumed load, the torque for either motor or generator is,—

$$Torque = \frac{Shaft\ hp \times 5250}{r.p.m.}$$

Various values of output may be assumed, giving complete characteristics for all speeds and torques. The performance of an induction machine under conditions of motor and generator operation are compared in Figs. 7 and 8. Constant line voltage and frequency have been assumed, since this is the most common condition. At less than full load the performance as a generator is very little different from that as a motor, for the same output. The motor torque and slip are somewhat less than for the generator, while the power-factor and line current are slightly greater, for the same output.

Beyond full load, the pull-out point is generally the only point of interest. Having assumed such values of output that the curves of Fig. 9 may be obtained for a motor or generator, the circle diagram need not be constructed to obtain the maximum torque. The maximum torque in synchronous watts, and to the proper scale, is represented on the circle diagram of Fig. 5 as $GH$ for a motor, $JK$ for a generator. The point $G$ is found by drawing a perpendicular to

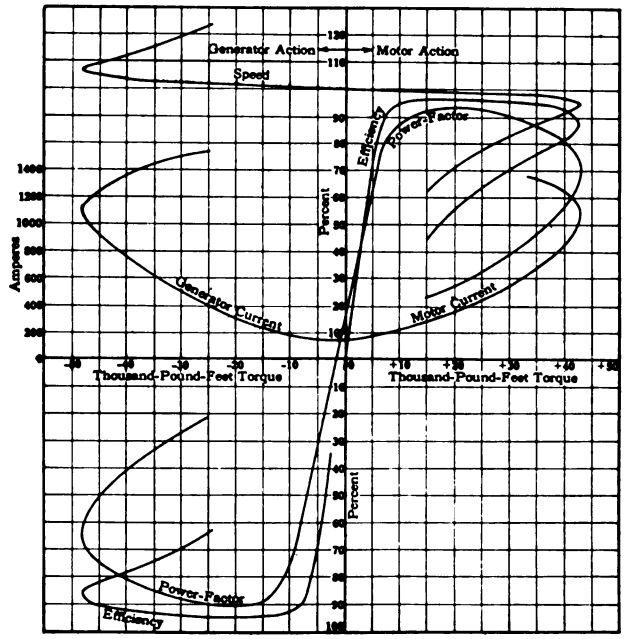


FIG. 8—COMPLETE OPERATING CHARACTERISTICS OF A MACHINE AS A MOTOR AND GENERATOR, LINE VOLTAGE CONSTANT

the primary loss line through the center of the circle; producing this line to intersect the under side of the circle locates point $K$. An approximate value for $x$ at the maximum-torque point is:—

$$x_t = \frac{D}{2}\left(1 \pm \frac{r_1}{z}\right)$$

where $x_t$ is the value of $x$ at maximum torque, $r_1$ is the primary resistance per phase and $z$ is the total impedance per phase in terms of the primary.

As a motor, the sign is negative, as a generator the sign is positive. Having $x_t$, the values of $y$ and

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all currents, losses, torques, etc., may be found as for other load points, and the maximum torque determined. Note that the maximum torque as a generator considerably exceeds that as a motor, the difference being greater for machines having a high value of primary resistance compared to the total impedance. For a motor, the torque available at the air-gap is proportional to the watts input from the line, less the watts lost in the primary, while for a generator this torque is proportional to the watts output to the line (negative power input) plus the primary loss in watts.

### APPLICATION AND USE

Induction generators are best suited for circuits which normally carry leading currents, or where such leading current components can readily be supplied. The usual arrangement is to connect the generator to a system in parallel with synchronous motors and alternators, suitably excited. The synchronous machines supply not only their own excitation, but also that for the induction generator. In certain cases, a part of the reactive exciting current can be supplied

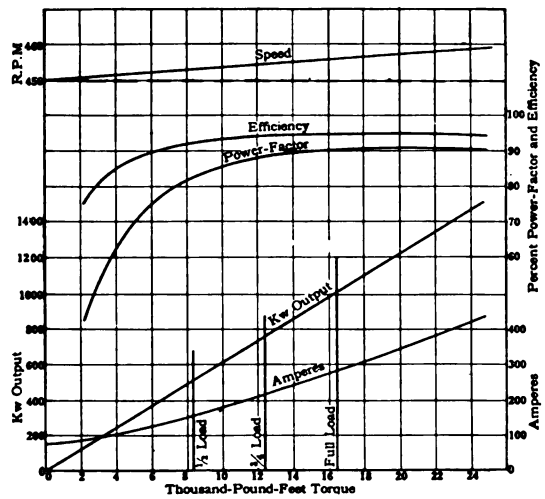


FIG. 9—INDUCTION GENERATOR CHARACTERISTICS ON A TORQUE BASIS

by the charging current of large underground cable or overhead transmission systems. For circuits in which the line current normally lags the voltage, and where the exciting current cannot be obtained from a nearby source, the induction generator is at a disadvantage when compared to the synchronous type.

The great developments in power generation have been toward large central stations, with synchronous generators, transformers, auxiliary exciting circuits and extensive control and protective equipment. The proper operation of such a station requires attendance of an expert kind. On the other hand, the small and isolated plant offers an application for automatically-controlled generators, which may be of the induction type. The relative simplicity, reliability, and cheapness of this type of installation may make profitable an independent source of power which would otherwise be wasted. The induction machine is simple and rugged, particularly when a squirrel-cage rotor is used, and there is no attached exciter. Little supervision or control is required, the connection to the line often being made through permanently connected transformers, with the generator supplying power to the system in proportion to the power available to drive it above synchronism.

Spare induction motors may be used as induction generators, and have been so used where a seasonal excess of water power was available. An arrangement with the power company secured for the customer a rebate in proportion to the power returned to the company's circuits, the consumer using and paying for power through regular connections.

The induction generator is less practical for slow-speed than for high-speed applications, since the exciting kv-a is greater for slower speeds, and excessive development charges may be required for a speed lower than that for which induction motors are generally designed. For these applications, the higher cost of automatic control equipment for synchronous generators may not prove disadvantageous. Unfortunately for the induction generator, the majority of small, isolated water power plants are low head, slow speed. Coupled with the excitation limitations, this disadvantage has resulted in a more general use of synchronous generators. Certain circuit and power source conditions continue to offer, however, a field for the induction type of generator.

The advantages of the induction generator may be summed up as follows:—

1—Low first cost; the construction is simple, since no exciter is needed and a simple squirrel-cage rotor may be used.

2—No synchronizing is required. The control for automatic operation is simpler and less expensive than for an equivalent synchronous machine.

3—It is easily designed against injury at runaway speed.

4—Overspeeding causes no over-voltage or increase in frequency, since the excitation is from the line and the speed frequency relation is variable as for an induction motor. The line voltage may be remotely controlled by proper excitation of the synchronous machinery from which the generator is in turn excited.

5—There is no tendency to supply power to a line fault, since loss of voltage means loss of excitation, and only a brief transient will be experienced.

6—Overloading is impossible with the energy output restricted by the gate opening, since the excitation is fixed by the design characteristics.

7—In case there are several generators operating in parallel, the severe hunting sometimes associated with the synchronous type cannot occur: the coupling between line frequency and rotor speed is of the nature of a friction rather than an elastic type of coupling, tending to damp out any system oscillations.

8—In common with the induction motor, the induction generator is largely passive as to wave shape, and tends to suppress voltage harmonics on the line.

The principal disadvantages are:—

1—The cost and weight for slow speeds are greater than for the equivalent synchronous generator and exciter.

2—Reactive kv-a for excitation must come from the line, or additional synchronous capacity must be installed at the generating point.

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# Protective Grounds

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GROUNDS, whether installed to protect apparatus, or to reduce personal hazard, are effective only if and when the maximum voltage between the grounded point and the earth is kept at a comparatively low value. This potential difference is a function of the ground resistance and of the current that can flow through it; these characteristics, in turn, being determined by the nature of the earthing connection and by the current carrying capacity of the conductors.

**It can by no means be assumed that a grounded conductor is always at approximate earth potential. If, for example, the circuit characteristics are such as to permit a current flow of 25 amp., through a 10 ohm ground, a potential difference of 250 volts will at once be established. Neither of these values is excessive or abnormal, and it is evident that under many conditions much higher voltages can be maintained. Thus a 2300 volt line earthed through a 23 ohm resistance, which is not at all unusual, would need to pass only $\frac{2300}{23}$ = 100 amperes in order to maintain full voltage.**

More often than not apparatus and arrester grounds are installed in a hap-hazard manner and tested perfunctorily, if at all. The larger systems, utility and industrial, are voluntarily undertaking to better this condition. Smaller enterprises, however, are in some cases reluctant to follow the rules suggested by regulatory bodies, due perhaps to their failure to recognize that proper grounding is a real engineering problem.

### CLASSIFICATION OF GROUNDS

Grounds may be classified according to application, as follows:

*Arrester Grounds*—To provide a free path to earth for abnormal surges which have broken down the arrester gaps.

*Feeder Grounds*—To maintain a low ground potential on certain parts of generating and distribution systems, such as the primary or secondary neutrals, and the like.

*Instrument Circuit Grounds*—To maintain low ground potential in the coils of instruments and related apparatus.

*Frame Grounds*—To maintain the frames of apparatus and the cases of instruments and meters at a potential not hazardous to life.

On a construction basis, grounds may be classified as:

*Driven Grounds*—Consisting of pipes or rods driven into the ground.

*Buried Grounds*—Consisting of plates or other masses of metal buried in dug pits.

*Pipe Grounds*—Consisting of connections made to more or less extensive water pipe systems.

*Arrester Grounds*—Distribution system lightning arresters are ordinarily installed at transformer settings and at intervals on lines in exposed localities, such as high hills and mountains. It is often possible in urban communities to make use of water-pipe grounds by running the leads to hydrants and fire plugs, but in the majority of cases driven grounds are necessary. While it would be desirable to have a resistance of not more than two or three ohms, such values are ordinarily unattainable and a practical maximum of 25 ohms has been widely accepted. There is, however, a tendency toward making 15 ohms a limiting value. It should be noted that inasmuch as most distribution arresters have impedances lower than 25 ohms, such a value for the ground reduces the discharge ability to less than 50 percent. Surveys by power companies show that even this high value of 25 ohms is often exceeded, and that driven grounds of 100 ohms are very common. In isolated cases the values found were far higher, running into 2000 or 3000 ohms, and occasionally approached infinity. These surveys indicated the necessity of testing each ground as installed and the desirability of periodic inspection in localities where variables are apt to be introduced by soil or climatic conditions. In urban districts, the unfavorable effect of the high resistance of individual arrester grounds, is to some extent offset by the fact that several units are usually installed on each feeder.

Station arresters have a much lower impedance and higher discharge ability than line arresters, and protect costlier equipment. It is therefore essential that their earth resistance be very low, never exceeding three or four ohms and preferably being a small fraction of one ohm. This value can seldom be obtained by driven grounds, and often not by plain buried grounds. In that event, the water-pipe system or treated grounds must be used.

*Feeder Grounds*—There is essentially no difference between feeder and arrester grounds, low resistance being required for either. The arrester earth connection will, however, carry only transient discharges lasting for an extremely brief period (a few microseconds) while feeder grounds may be subjected to leakage of considerable magnitude for long periods of time. It is evident, therefore, that for the latter, continuous carrying capacity must be considered, and allowance made for the increase of resistance due to the drying out of artificial grounds. Furthermore, the feeder ground is, so to speak, the last line of defense against dangerous voltages on the utilization lines and equipment.

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Present common practice to the contrary notwithstanding, installations of this type should be made with due regard for the maximum value of current which under any condition might be forced through the ground resistance. This may, on large capacity systems, be several thousand amperes. The voltage drop should be kept to some safe value, though this is difficult of accurate definition because of the many variables involved. It is, however, often assumed that voltages under 150 are non-hazardous, and on that basis, the ground resistance in ohms should not be allowed to exceed 150 divided by the available current. Thus, for example, if a line were fused to carry a maximum of 10 amperes, the ground might have a resistance of 150/10 = 15 ohms and still afford reasonable protection. If the current could rise to 100 amperes, the resistance should theoretically be 150/100 = 1.5 ohm, a value which is hard to obtain and, still harder, to maintain.

Although the maximum maintained flow of ground current is limited by the fuses or circuit breakers in the lines, it is evident that these protective devices cannot function instantaneously. The momentary rush of

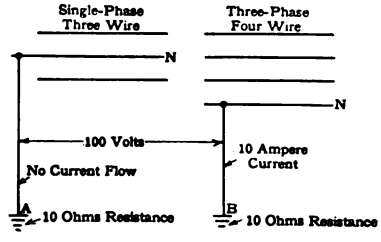


FIG. 1—SCHEMATIC DIAGRAM SHOWING POSSIBILITY OF GROUNDS BEING AT UNEQUAL POTENTIAL

current may set up voltages far in excess of the values calculated as above. This hazard would be a very real one, were it not for the fact that ordinarily several ground connections are installed in parallel. Thus, in a single-phase, three-wire system, the neutral will be connected to ground at each of the transformers, and again at each service fed from the secondary section involved. The service grounds will ordinarily be to water pipes, so that the collective resistance is very low. On the other hand, it must be remembered that this is not necessarily true in sparsely settled communities or on farm lines.

*Instrument Circuit Grounds* are used only for switch board work. While their importance should not be minimized, the possibilities of trouble here are greatly reduced by the fact that the wiring is all in conduit or compactly installed on the back of the switchboard. There is little chance of contact with high-powered feeders, while the circuits themselves are of such low capacity that the ohmic drop to ground can never be very high.

*Frame Grounds*—Switchboard instruments sometimes have their cases grounded in order to drain off static which might interfere with the operation of the measuring elements. Certain high voltage types require a substantial ground in order to eliminate the hazard incident to accidental contact between the coils and cover.

Motors, generators and other apparatus should have the frames substantially grounded in order to eliminate any hazard which might arise from accidental contact between the coils and iron. There are spe-

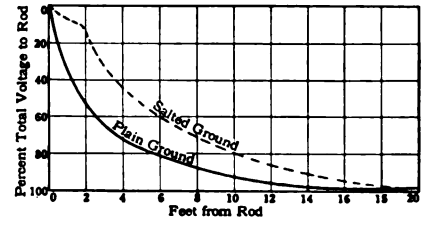


FIG. 2—TYPICAL POTENTIAL GRADIENT CURVES

cial cases where this cannot be done, and these must, of course, be treated in a class by themselves.

It might be assumed that a motor or a generator standing on a wet concrete floor would be adequately grounded without any special leads, but this often is not the case and wires must be run from the holding down bolts or housing studs to conveniently adjacent structural steel or to water pipes. Pole or platform-mounted transformers should not have their tanks grounded, as the hazard to the linemen is increased by this practice. On the other hand, in a substation installation where the tanks are accessible, the rule for motors should be applied.

## VOLTAGES BETWEEN DIFFERENT GROUNDS

Considerable difference in potential may exist between ground rods or conductors, due to the difference in ohmic drops. This is shown schematically in Fig. 1. *A* is a grounded neutral on a three-wire, single-phase system. Ordinarily no current will flow through it.

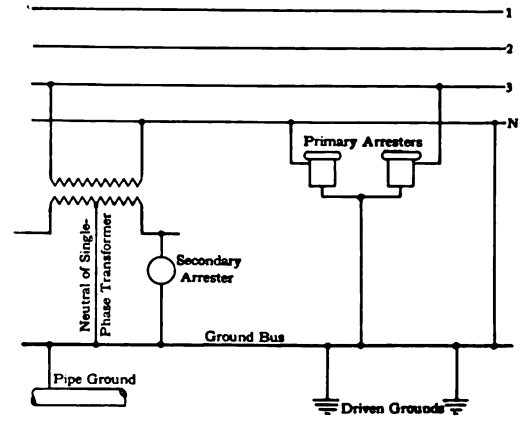


FIG. 3—A SINGLE BUS USED AS A COMMON GROUND FOR VARIOUS PIECES OF ELECTRICAL APPARATUS

so that no potential difference exists between the middle conductor and the earth. *B* is the grounded neutral of a three-phase four-wire system through which a portion of the system unbalance flows, due to the inadequacy of the neutral conductor itself. With 10 amperes flowing through a 10 ohm ground, 100 volts would exist between *A* and *B*.

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With larger values of current or resistance, the potential difference between *A* and *B* may assume hazardous proportions. Any attempt to overcome this condition by bonding may raise the secondary neutral to a dangerous voltage. Instances of severe shocks from the neutral, even when no metallic contact existed between it and the primary have been reported.

### VOLTAGE GRADIENT FROM GROUND RODS TO THE EARTH

It has been well established that from 90 to 95 percent of the resistance of a driven ground exists within a cylinder of earth with a radius of usually not over 10 feet about the rod as an axis. When a current is flowing, the greatest drop is therefore near

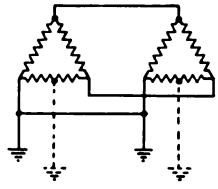

FIG. 4—METHOD OF GROUNDING PARALLEL THREE-PHASE DELTA TRANSFORMER BANK

the electrode, with a typical potential gradient curve like that shown in Fig. 2. The actual dimensions of this curve depends upon the characteristics of the soil, but is fairly independent of the magnitude of the impressed voltage. If this were high, say 200 volts, a potential difference of about 160 would exist between the rod and the earth at a distance of 4 feet. It should therefore not be erroneously assumed that it is impossible to receive a shock from a ground rod.

It is interesting to note the effects of lowering the resistance by the addition of salt. The dotted curve in Fig. 2 represents the gradient under this condition, and indicates that the salt treatment virtually increases the diameter of the ground rod.

### COMMON GROUNDS

There is, generally speaking, no objection to the grounding of all of the above classes of apparatus to a common bus, as shown in Fig. 3, which is in turn thoroughly grounded in several places so as to be at earth potential. A three-phase delta bank can of course be grounded only at one point, this being either the middle of one winding or else one corner of the delta. Two banks in parallel must have the grounds located in corresponding positions. This is shown in Fig. 4. In this case one ground should be sufficient, unless the two banks are a considerable distance apart.

It is not desirable, and in some states not permissible, to use artificial common grounds for arresters and feeders. The reason is quite obvious, for a severe discharge through the arrester might raise the potential of the grounding leads to a value destructive to the other apparatus. This action is sometimes referred to as the "arrester backing up".

### SIZE OF GROUND LEADS

Ground leads must necessarily be large enough to carry the current with minimum voltage drop, and to resist mechanical injury. Splices underground should be avoided. Individual feeder grounds should not be smaller than No. 6 wire. Some states permit the use of No. 10 where several grounds are in parallel; usually, however, with the provision that at least one conductor be No. 6.

The combined capacity of the ground leads on an alternating-current system should be not less than 20 percent of the conductor to which they are attached, though some rulings do not require wire larger than No. 0. Distribution arrester leads should be at least No. 6 wire, while station arrester leads should be larger.

This whole matter of ground conductors should be given careful thought, and in no event should the carrying capacity be so small as to produce excessive voltage drops, even under the most adverse conditions.

### GROUND CHARACTERISTICS

*Size and Spacing*—The characteristics of grounds of any type at times appear to be erratic in the extreme and to adhere to none of the basic laws which govern the flow of current in other circuits. Thus, the resistance varies directly with neither the size, number or material of the ground electrodes, and it is difficult to pre-determine with even approximate accuracy the results of changes in their design.

This apparent confusion disappears to a large extent if the electrodes and the earth, as a whole, are reduced to an equivalent circuit consisting of two conductors joined through an infinite number of paths, such as that in Fig. 5. These paths have various resistances, but for any given locality the distribution

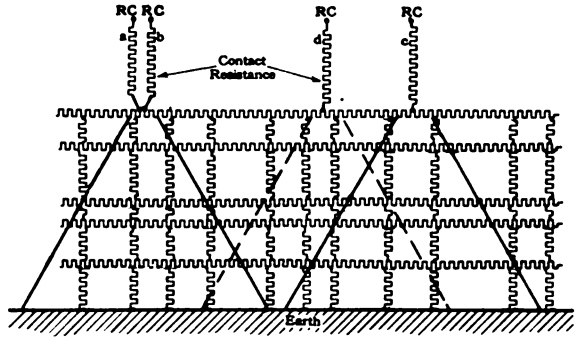


FIG. 5—SCHEMATIC ARRANGEMENT SHOWING GROUND CURRENT PATHS

throughout the mass is fairly uniform. The current leaving any ground rod first passes through the contact resistance, determined by the size and nature of the electrode surface, and then divides into a multiplicity of paths that lead to the earth itself. Thus, from the ground rod at *a*, the current passes through the resistance *RC-a* and then fans out, most of it flowing within the area indicated by the heavy solid lines. If a second rod *b* be driven in close proximity to *a*, the contact resistance *RC-a* and *RC-b* will be in parallel, but the area within the heavy lines will be unchanged. One would expect, then, that a second ground

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rod would reduce the resistance a little, inasmuch as the contact drop is halved, but that the total ground voltage drop would decrease only a comparatively small amount.

If the second rod be driven at *c*, a considerable distance away, it will give access to an entirely new section of earth, and it would be expected that the total resistance would now be reduced approximately one half. Furthermore, intermediate values should be obtained at some point *d* between *a* and *c*.

Actual tests give results that adhere closely to what might be expected from the foregoing, maximum effectiveness in multiple grounds being obtained only when the spacing between them is six to ten feet.

Driving a ground rod to greater depths would be covered by the same theory, and tests show that the decrease in resistance is by no means in direct proportion to the rod length. This holds true regardless of the fact that the moisture content is greater as the lower strata are reached. Increasing the size of the ground pipe decreases the contact resistance but does not open up new areas of earth. It follows that the decrease in the total resistance is much less than the increase in pipe area.

To summarize, then, increasing the size of any electrode reduces the resistance, but not in direct proportion to the increase in contact area. Increasing the number of rods decreases the resistance in proportion to their number only when the spacing is great enough to eliminate any overlapping of paths through the earth. Practice shows that under normal conditions of earth resistivity not much is gained by driving a pipe deeper than 10 feet, nor increasing the diameter over 1 inch. As a matter of fact, the latter dimension is based upon mechanical strength to resist buckling during driving, and the electrical characteristics would not be greatly changed by the use of ¾ inch or even ½ inch pipe.

These general principles governing the size and spacing, though referring specifically to driven grounds, apply as well to buried plate grounds.

Current through the mass of the earth flows, to a limited extent, through the solids of which it is composed, and very largely through the surrounding moisture. It follows, therefore, that the resistance characteristics are governed largely by the amount and chemical composition of the ground water and by the solids only so far as they, by solution or chemical action, change its conductivity.

Pure water is a very poor conductor. In localities where the soil consists of insoluble sands or gravel, the ground water is little affected, and the specific resistance is accordingly high. It is difficult to install satisfactory grounds in such places, even if the electrodes are submerged.

On the other hand, made earth, consisting of cinders, refuse, decaying vegetable and animal matter and the like, infuses into the water a variety of components that lower the resistance and permit the easy installation of satisfactory grounds. Swampy land, particularly where the salt content is high, is a good conductor. Between the two extremes, the specific resistance has corresponding intermediate values.

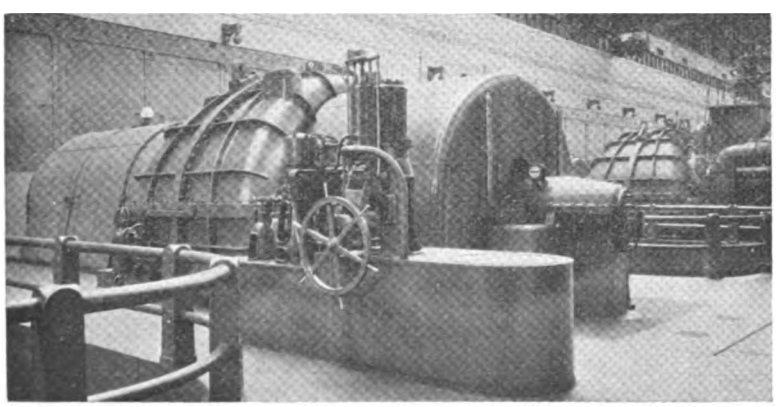
The amount of water is of importance up to the point where each solid particle is covered with a film of moisture. Beyond that point, any increase affects the resistance but slightly.

Inasmuch as only the deeper layers of earth are permanently moist, it is essential that grounding electrodes be located in them. There is, of course, variation with climatic conditions both geographic and seasonal, but it should require but little investigation to determine whether or not a proposed depth is ample. Inasmuch as frozen earth has high resistance, ground electrodes should be below the frost line.

It may ordinarily be assumed that the extensiveness and depth of municipal water systems reduce the resistance of such grounds to a very low value. Exceptions to this are rare. Isolated water systems, such as those on a farm, are not so reliable, and these should be subjected to the same tests as an artificial ground.

*(To be Continued)*

## Turbines for Colfax Installed



Two 41 250 kw, single cylinder turbines have just recently gone into successful operation in the Colfax Station of the Duquesne Light Co. These turbines operate at 1800 r.p.m. on steam superheated 214 deg. F. at 260 pounds gage at the throttle and against a back pressure of one inch of mercury absolute. The turbines are designed for bleeding at four points for feed water heating. Oil governors, recently applied to units of such size, are used.

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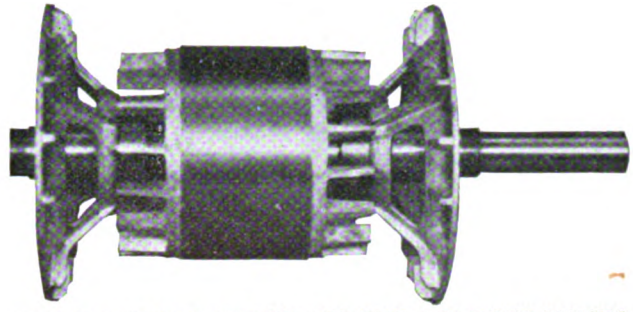
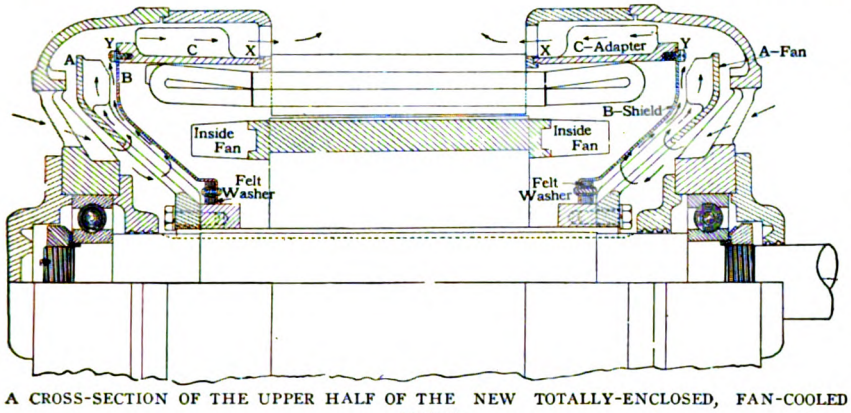
# Enclosed, Fan-Cooled Motors

C. C. NELSON
Industrial Motor Engineering Dept.,
Westinghouse Electric & Mfg. Co.



A ROTOR ASSEMBLY SHOWING THE FANS AND INSIDE BLOWERS

WITHIN the last year a new type of enclosed motor has come into prominence and, because of its outstanding advantages for those applications requiring totally enclosed motors it has become extremely popular. Essentially, the fan-cooled motor is fairly simple in that fan blowers are mounted on the motor shaft and the air passages so constructed as to give the motor the benefit of the circulating air.




A CROSS-SECTION OF THE UPPER HALF OF THE NEW TOTALLY-ENCLOSED, FAN-COOLED MOTOR

In general, two methods of ventilation have been employed on fan-cooled motors, namely:—

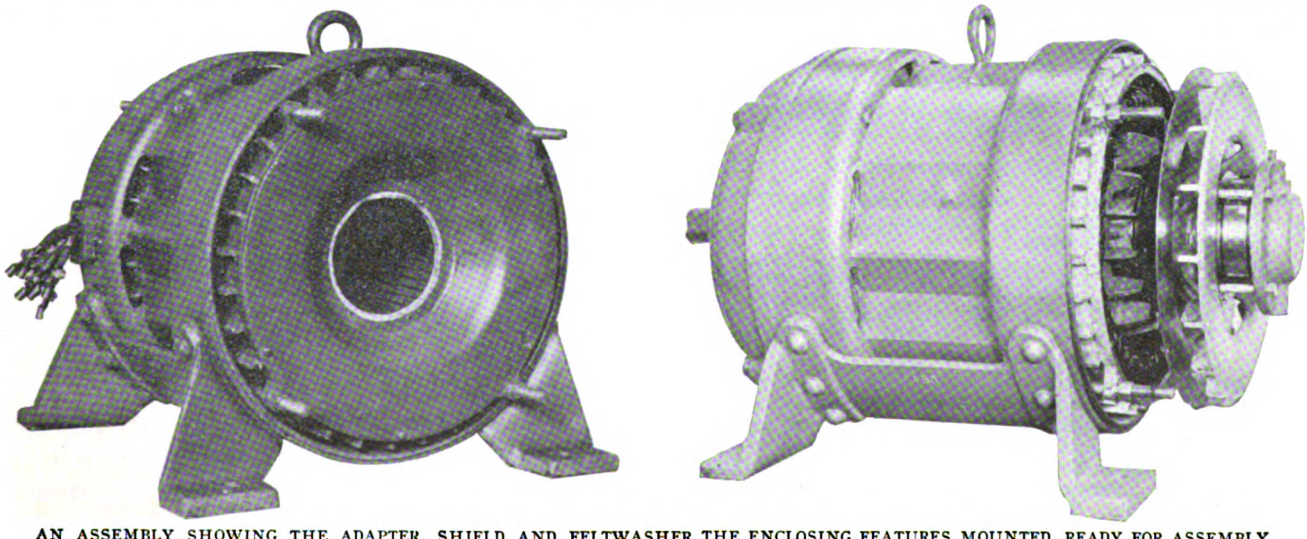
Double-end ventilation
Single-end ventilation

Those of the first division draw air in from each end (through bracket openings) and force it out over the core in the middle of the motor. Those of the second division draw air in from one end and force it through the motor over the core and out the other end.

A section of a double-end ventilated, fan-cooled, squirrel-cage motor is shown in the sketch. Air is drawn in from both ends by the fans *A* which are secured to the shaft and rotate with it. The air is drawn down toward the shaft and from there sweeps across the copper shields *B*, over the adapters *C*, and out across the core of the motor which is exposed directly to the surrounding air. Within the motor, blowers mounted on the rotor serve to agitate the internal air, thereby facilitating the conduction of heat through the shields and adapters. This scheme of ventilation is simple and effective. The windings and inner parts are fully protected from dirt, dust and other foreign matter which may do damage to the vital parts. The adapter is carefully fitted at *X* and the shield is fitted at *Y*. At the shaft a felt washer is fastened to the shield producing an effective enclosure.

The result is a fully-protected motor with the direct exposure of the heat generating core retained. Standard motor parts are employed with the addition of enclosing details, such as adapters, shields and fans. The advantages to be attained may be summarized somewhat as follows:—

1—For the same output, the size of the motor is considerably reduced, thereby reducing the cost from that of the



AN ASSEMBLY SHOWING THE ADAPTER, SHIELD AND FELTWASHER THE ENCLOSING FEATURES MOUNTED, READY FOR ASSEMBLY

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ordinary totally-enclosed motor, and space requirements. For small sizes such as 5 hp, 6 poles, the benefit of fan cooling is not so pronounced and the ordinary enclosed motor is used to advantage.

2—Standard motor frames and parts are employed, thereby retaining standard overall lengths and heights.

3—Double-end ventilation, in addition to directly exposing some of the heat generating parts, allows both ends of the motor to operate at approximately the same temperature, thereby producing proper heat distribution and reducing the possibility of extremely hot spots.

4—A pleasing and well-balanced appearance is obtained.

This type of motor has already proved its worth in various applications. Its advantages over the old non-ventilated type are beneficial in such applications as manufacturing, coke plants and the oil industry. Its success indicates that there will be further demand and that a large number of the older enclosed motors will gradually be eliminated.

# Contact Resistance of Electric Switching Apparatus

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IT is generally recognized that the current rating of a switch is determined by the maximum permissible temperature at the contact. The contact temperature must be kept below a certain value, in order to prevent excessive oxidation and eventual burning of the contacts. The temperature rise of the contact does not depend, however, solely upon the contact loss, as is very often assumed, but is greatly influenced by the

1—Total $I^2R$ loss of the switch,
2—Cooling surface available for heat dissipation,
3—Amount of material available to carry the heat from the hot spots to the cooling surfaces.

Most of the heat that is generated at the contact, must be carried away through the shunt and the contact support. The loss and temperature of these two conductors, therefore, must be much lower than that of the contact itself, so as to permit efficient heat dissipation. The highest current rating of the switch, i.e., a minimum weight per current unit, is obtained by providing adequate material for heat conductivity, in order to reduce the temperature difference between the contact and the cooling surface to a minimum.

Little difficulty will be encountered in calculating the temperature of a switch, if both loss and cooling surface are known. However, there is much uncertainty with regard to the contact loss, which influences the contact temperature more than anything else. Tests show that this loss is directly proportional to the contact resistance, and may be expressed by the following equation:

$$W = I^2R$$

where $W$ = contact loss, in watts
$I$ = current carried by the contact,
$R$ = contact resistance.

It is generally known that the contact resistance is some function of the contact pressure; it decreases, for instance, if the pressure is increased, and vice-versa. It is also found that the contact material and the surface structure highly influence the contact resistance. But very few, if any, data are available as to the exact relation existing between contact resistance and contact pressure, etc. The fact that so many tests have failed to reveal the true relations, indicates that various factors influencing the contact resistance were not known, and consequently neglected.

The writer believes that such an important problem cannot be solved unless studied theoretically, and

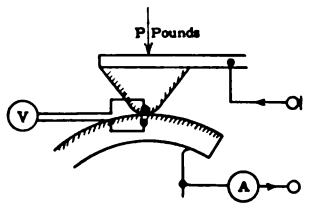


FIG. 1—ARRANGEMENT FOR MEASURING CONTACT DROP

therefore tries to give in the following a complete analysis of the contact resistance.

## CONTACT RESISTANCE OF SINGLE-POINT CONTACT

If a current $I$ passes through a contact arrangement as shown in Fig. 1, it is possible to measure a voltage drop across the contact which is proportional to the current and may be expressed by

$$E = IR$$

This voltage drop is caused by the contact resistance R, the nature of which is similar to that of any solid metallic conductor. Practically all the resistance occurs right at the contact surface and is caused by the tiny irregular projections which actually make up the contact surface. No matter how carefully a contact is ground, it is impossible to obtain a perfectly smooth and flat surface; a sufficiently magnified view of the contact shown in Fig. 1 will reveal a surface structure similar to that of Fig. 2.

At low pressures the contact takes place at one point only, and the current has to be carried by one of the irregular projections or pyramids shown in Fig. 2. The contact resistance, therefore, is considered equivalent to the ohmic resistance of two minute

*A paper, dealing with the same subject, was published by the author in the "Bulletin des Schweizerischen Elektrotechnischen Verein," Jahrgang 1924, Heft 3. Some equations and curves of the present article are taken from above paper. See also paper published by F. W. Harris, Electrical Contact Resistance—THE ELECTRIC JOURNAL of July 1913, page 637. Also by G. E. Luke, The Resistance of Electrical Connections—THE ELECTRIC JOURNAL of February 1924, page 66.

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points or pyramids with the length $x_1$ and $x_2$. These pyramids are flattened out by the contact pressure $P$ and will touch with a surface

$$S = \frac{P}{\sigma}$$

where $\sigma$ = the crushing strength of the contact material.

Of course, it would be impossible to control the shape and size of such an irregular pyramid, and it would be even harder to calculate its electrical resistance. It is therefore proposed to simplify the prob-

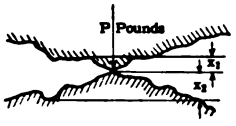


FIG. 2—DIAGRAMMATIC MAGNIFICATION OF A CONTACT

lem by assuming a pyramid of straight sides and of square base, as shown in Fig. 3. This simplification will have no effect upon the general character of the resistance curve.

With reference to Fig. 3, the contact resistance, i.e. the resistance of two contact pyramids, is equal to

$$R = 2\rho \int_0^x \frac{dx}{y^2},$$

where $\rho$ = the specific resistance of the contact material.

It is further the case that

$$y = a\frac{l-x}{l}$$

and therefore the contact resistance

$$R = 2\rho \frac{l^2}{a^2} \int^x \frac{dx}{(l-x)^2},$$

or

$$R = 2\rho \frac{l^2}{a^2}\left(\frac{1}{l-x} + K\right).$$

For $x = O$, the resistance $R$ must be zero. The constant K, therefore, is $K = -\frac{1}{l}$, giving finally

$$R = 2\rho \frac{l^2}{a^2}\left(\frac{1}{l-x} - \frac{1}{l}\right) \ldots\ldots\ldots\ldots (1)$$

This equation is very interesting in that it reveals the relation between contact resistance and the flattening of the pyramid. It shows that the resistance decreases as the pyramid is more and more flattened by increasing contact pressure. It also illustrates very clearly that the contact resistance must increase to an infinite value if the dimension $x$ in Fig. 3 is equal to $l$, i.e. if the contact pressure is reduced to zero.

It now remains to substitute the contact pressure $P$ for the length $x$, in order to obtain the direct relation between contact pressure and contact resistance. For this purpose the contact pressure is determined as

$$P = \sigma y^2 = \sigma a^2\left(\frac{l-x}{l}\right)^2,$$

where $\sigma$ = the crushing strength of the contact material.

Thus we obtain

$$x = l\left(1 - \frac{1}{a}\sqrt{\frac{P}{\sigma}}\right),$$

or, substituting this value for $x$ in equation (1) gives a contact resistance equal to

$$R = 2\rho \frac{l}{a^2}\left(\sqrt{\frac{a^2\sigma}{P}} - 1\right)$$

While practically all the factors of this equation are known, it would be impossible to determine the dimensions $a$ and $l$, because they depend upon the finish of the contact surface. It is therefore proposed to replace them by constants $c_1$ and $c_2$, which are to be determined by test. The contact resistance therefore may be expressed as

$$R = c_1\sqrt{\frac{\sigma}{P}} - c_2, \text{ whereby}$$

$$c_1 = 2\rho\frac{l}{a}$$

$$c_2 = 2\rho\frac{l}{a^2}$$

Tests made with various materials which are referred to later, show that the constant $c_2$ may be neglected, so that the equation for the resistance of a single-point contact takes the following shape:

$$R = c\frac{1}{\sqrt{P}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Fig. 4 gives typical resistance curves as obtained from the above equation. It will be noted that the above equations are developed by assuming the contact pyramids gradually crushed with increasing pressure, thereby stressing the material beyond the elastic limit until it starts to flow. The relation between contact pressure and contact resistance, therefore, will be different if the contact pressure is decreased instead of increased. It is obvious that in this case the contact resistance must be lower, because the active con-

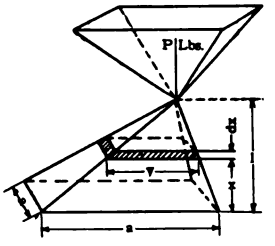


FIG. 3—A CONTACT REPRESENTED AS THE CONTACT OF THE APEXS OF TWO PYRAMIDS

tact surface $y^2$ and the number of contact points are larger and correspond to a pressure $P$ higher than the actual contact pressure. A complete cycle of pressure variations, including both pressure increase and decrease, is shown in Fig. 7.

The crushing of the contact points naturally is only possible at relatively high specific pressures. Low contact pressure, in conjunction with large areas, will give a resistance curve which is reversible, i.e., the contact resistance for increasing and decreasing pressure is the same. It is quite possible to confirm this experiment, provided the contact surfaces are not disturbed during the test.

### CONTACT RESISTANCE OF MULTIPLE-POINT CONTACT

While in the previous paragraphs it was assumed that current has to be carried by one contact point, it must be added that such conditions will occur at low contact pressure only. The design of the contact and the finish applied to the contact surface may be such that an increase in contact pressure will not only cause a flattening of the contact pyramid, but will also result in an increase in contact points. This is particularly true for contact pressures higher than ten pounds.

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Considering the various contact arrangements designed for different purposes the various designs can be segregated into two distinct classes:

1—The single point contact or rigid contact finger.

2—The multiple-point contact as obtained with the flexible brush contact, for which an increase of contact pressure results in an increase of contact points without flattening of the contact pyramids.

If the total contact pressure $P$ is assumed to be equally divided among $n$ contact points with a pressure of

$$P_n = \frac{P}{n}$$

there results a resistance per contact point

$$R_n = \frac{c_1}{\sqrt{\frac{P}{n}}} - c_2,$$

and therefore a total contact resistance of

$$R = \frac{R_n}{n} = \frac{c_1}{\sqrt{nP}} - \frac{c_2}{n}$$

The second member of the above equation is comparatively small and can be neglected, so that

$$R = c\frac{1}{\sqrt{nP}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The relation between contact pressure and number of contact points is shown in Fig. 5. It shows that the resistance decreases with the square root of the number of contact points. A contact with nine contact points, for instance, has a resistance of one third of that of a single-point contact, provided the total pressure is the same.

Quite interesting is the extreme case where an increase in contact pressure results in a proportional increase of contact points. In this the contact pressure is equal to

$$P = c_3 n$$

and the equation for the contact resistance changes to

$$R = \frac{c}{\sqrt{\frac{P}{c_3}P}}$$

or, collecting the constants

$$R = c\frac{1}{P} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

All these considerations show very clearly the desirability of a maximum number of contact points. The problem, therefore, is to determine the best contact shape. While it is not within the scope of this paper to go into details, the following may be said with regard to the contacts shown in Figs. 6 (a), 6 (b), and 6 (c).

Any solid contact that is not self-aligning must be considered as a single-point contact, no matter how carefully adjusted. The actual contact surface that aids in carrying the current has little, if anything, to do with the flat contact surface shown, for instance, in Fig. 6 (b), and is strictly a function of the contact pressure.

If the contact is carefully ground, the actual contact surface will naturally be larger than that obtained with the above equation. The commercial switch, however, will never permit such ideal conditions, and if, by chance, they are obtained at the factory, it will be impossible to maintain them in service. The so-called lining-up of the contacts serves only to insure a more or less regular contact wear; the contact resistance is little influenced by doing this.

The width of the contact is determined by the permissible contact wear and the material necessary to carry the current to the contact. If it were for

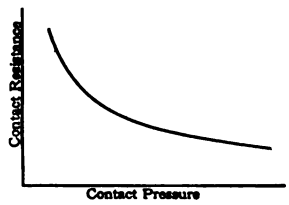


FIG. 4—A CALCULATED PRESSURE-RESISTANCE CURVE

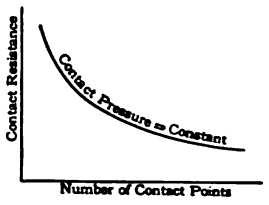


FIG. 5—A CALCULATED CONTACT-RESISTANCE CURVE

the contact resistance alone, the dimensions of the contact could be reduced considerably below those generally adopted.

If the solid contact is self aligning, i.e., if the two contact surfaces can adjust themselves to each other, the minimum number of contact points is two. Under similar conditions the self-aligning contact, therefore, will have a contact resistance about 30 percent lower than that of the single-point contact. The flexible brush contact shown in Fig. 6 (c) has as many contact points as there are laminations. This kind of contact will give a minimum resistance for a certain contact pressure and is superior to the solid contact, provided the contact surface is kept clean. If the contact surface can not be kept clean, the brush contact will give poor results, because the low specific pressure of the laminations will not permit a thorough cleaning of the surface. The importance of a clean contact is obvious,

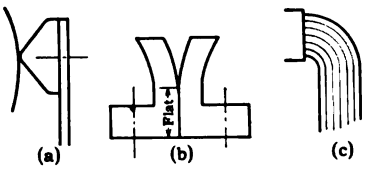


FIG. 6—VARIOUS KINDS OF COMMON CONTACTS

as is illustrated by subsequent curves. Experience has shown that the single-point solid contact with high specific contact pressure is more reliable and superior to the brush contact for heavy duty service.

## TEST RESULTS

While the equations developed in the preceeding discussion show the true character of the resistance curves, they do not give the actual resistance values; in other words, it remains to determine the constant $c$ of equations (2), (3) and (4). For this purpose a series of tests was made to determine the relation between contact resistance and contact pressure.

A special test equipment was built which would permit a gradual increase of contact pressure without

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disturbing the seat of the contact surface. This is a condition which must be satisfied, if the test results are to be consistent and of any value. The curves shown in Figs. 7, 8 and 9 represent average values obtained from a series of tests made with various contact shapes. The maximum variations were within 20 percent of the curve values. These test results refer

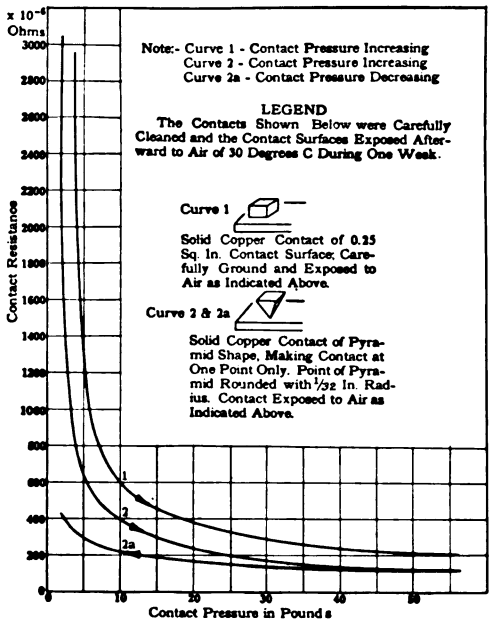
x 10⁻⁶ Ohms
Contact Resistance
Note:- Curve 1 - Contact Pressure Increasing
Curve 2 - Contact Pressure Increasing
Curve 2a - Contact Pressure Decreasing
LEGEND
The Contacts Shown Below were Carefully Cleaned and the Contact Surfaces Exposed Afterward to Air of 30 Degrees C During One Week.
Curve 1
Solid Copper Contact of 0.25 Sq. In. Contact Surface; Carefully Ground and Exposed to Air as Indicated Above.
Curve 2 & 2a
Solid Copper Contact of Pyramid Shape, Making Contact at One Point Only. Point of Pyramid Rounded with 1/32 In. Radius. Contact Exposed to Air as Indicated Above.
Contact Pressure in Pounds

FIG. 7

to copper contacts only; the resistance of other materials may be obtained by taking into consideration the specific resistance and the hardness of the respective contact materials. This, of course, is true for clean contacts only; dirty or oxidized contact surfaces will give altogether different results, and will be referred to later.

Figs. 8 and 9 illustrate the contact resistance of clean copper contacts of various shapes and finishes. The results may be summarized as follows:

1—The constant $c$ of equations (2), (3) and (4) seems to be more or less fixed, and independent of the shape of the contact surface; it is found to vary from (2.1 to 2.6) $\times 10^{-4}$, or to have an average value of $c = 2.3 \times 10^{-4}$ for clean copper contacts.

The somewhat higher value of curve 3 in Fig. 8 may be explained by the fact that this test was made with a carbon circuit breaker, the contacts of which were not carefully cleaned before beginning the test. It is very likely that the brush was slightly oxidized due to exposure to a temperature of about 20 degrees C. for several days.

2—The contact resistance is a function of the contact shape and decreases with increasing number of contact points. See also equation (3). The resistance $R$ for clean copper contacts is found to be

*a*—Single-point contact:

$$R = 2.3 \times 10^{-4} \times \frac{1}{P^{0.5}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

*b*—Multiple-point contact:

$$R = 2.3 \times 10^{-4} \frac{1}{P} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

Curve 5 of Fig. 8 looks like an extreme condition which may not be encountered very frequently. Contact 4 of Fig. 8 probably corresponds more closely to the resistance obtained with the commercial contact finger. Naturally it is very hard to know the correct value of the exponent of P. It may vary from 0.5 to 0.8 for the same type of contact depending upon the seat of the contact surface. The only safe way in such a case is to base calculations on the worst condition, i.e., to assume that the contact resistance is a function of $P^{0.5}$.

3—The contact resistance is a function of the number of contact points rather than the size of the contact surface. This is proven clearly by curves 1 and 3 of Fig. 8, which show that the one-fourth square inch surface of contact 1 gives a lower resistance than the brush contact of No. 3 with 4.4 square inches surface. Quite interesting is the effect of polishing the contact surface. Contact No. 2 was obtained by rubbing the clean and perfectly ground contact No. 1 against its mating contact until a high polish was obtained. This not only increased the constant $c$ but also reduced the exponent of $P$ from 1 to approximately 0.8.

### DIRTY AND OXIDIZED CONTACTS

The curves in Fig. 8 and 9 represent ideal conditions, i.e., their resistances are obtained with clean contact surfaces. The importance of clean contacts cannot be emphasized too much, because it influences the resistance more than anything else.

It will be remembered that the contact resistance occurs right at the contact surface; its value, there-

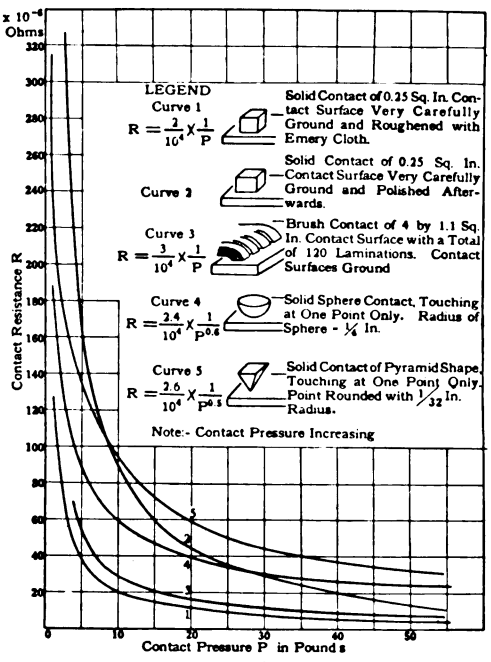
x 10⁻⁴ Ohms
Contact Resistance R
LEGEND
Curve 1
R = 2/10⁴ X 1/P
Solid Contact of 0.25 Sq. In. Contact Surface Very Carefully Ground and Roughened with Emery Cloth.
Curve 2
Solid Contact of 0.25 Sq. In. Contact Surface Very Carefully Ground and Polished Afterwards.
Curve 3
R = 3/10⁴ X 1/P
Brush Contact of 4 by 1.1 Sq. In. Contact Surface with a Total of 120 Laminations. Contact Surfaces Ground
Curve 4
R = 2.4/10⁴ X 1/P^0.8
Solid Sphere Contact, Touching at One Point Only. Radius of Sphere - 1/4 In.
Curve 5
R = 2.6/10⁴ X 1/P^0.5
Solid Contact of Pyramid Shape, Touching at One Point Only. Point Rounded with 1/32 In. Radius.
Note:- Contact Pressure Increasing
Contact Pressure P in Pounds

FIG. 8

fore, is determined by the material found at the surface rather than inside the contact. It is well known that the slightest amount of impurities added to a material increases its electrical resistance to a very large extent. An oxidized contact surface conse-

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quently may give a contact resistance that is more than one hundred times the value obtained with clean contacts.

The rate of oxidation is a function of the temperature and the time during which the contact surface is exposed. Copper contacts start oxidizing at room temperatures of 20 to 30 degrees C. This is clearly shown by the curves of Fig. 7 obtained with copper contacts No. 2 and 5 of Fig. 8, after exposure to air of 20 to 30 degrees C. for one week. Care was taken that the contacts were closed without any rubbing or wiping action, so as to measure the full effect of the copper oxide film. A comparison of Fig. 7 with the respective curves of Fig. 8 shows that the contact resistance of the oxidized contact is considerably higher than that of the clean contact, although the temperature to which the contact was exposed was never above 30 degrees C. The rate of oxidation increases rapidly with rising temperature; copper contacts, exposed to 100 degrees C. for about one hour, increased their resistance about fifty times.

There is a very noticeable difference between the single point contact No. 2 and the multiple point contact No. 1 of Fig. 7. The high specific contact pressure of the single-point contact crushes the oxide film more readily than the low specific contact pressure of the multiple-point contact. The single-point oxidized contact, therefore, will give a lower contact resistance than the multiple point contact, regardless of the fact that the latter has actually more active contact points.

The contact pressure has two distinct purposes. It not only must insure an intimate contact between the two surfaces as indicated previously, but it also must keep the contact surface clean. This latter function is very important and must be satisfied if the contact is to stand up in service. Fig. 7 shows that pressure alone does not insure clean contact surface. The cleaning of the contacts is a function of specific pressure times amount of rubbing or wiping. Contacts with high contact pressure and which have to carry high currents will naturally require less wiping action than contacts with low contact pressure. Any contact surface that has no wiping action, such as screwed connections etc., should be coated with a low resistance material that does not oxidize readily. Tinned connections, for instance, give good results and are superior to bare copper connections, although the tinned contacts may have a somewhat higher contact resistance than the clean copper contacts.

### CRUSHING STRENGTH AND CONTACT SURFACE

While there is no question that the contact surface is a function of the crushing strength of the contact material, it must be borne in mind that the surface structure and the general shape of the contact itself influence the size of the contact surface to a considerable extent.

Considering the crushing strength $\sigma$ from an electrical point of view, it must be defined as

$$\sigma = \frac{P}{y^2},$$

where $y^2$ represents only the part of the crushed surface giving intimate metallic contact. This may be illustrated more clearly by the following experiments:

A pyramid of soft copper similar to Fig. 3 was subjected to pressures varying from 100 to 10 000 lbs The originally sharp point of the pyramid was gradually crushed, and it was found that the size of the flattened surface increased in proportion to the applied pressure, as illustrated in Fig. 10. If we were to consider this surface from a purely mechanical standpoint, we would find a crushing strength of

$$\sigma_{mech.} = \frac{P}{y_m^2} = \frac{10\,000}{0.134} = 75\,000 \textit{ lbs. sq. inch for soft copper.}$$

or about 2 to 3 times the maximum tensile strength. It would be wrong, however, to assume that metallic contact occurs at each point of the crushed surface. No matter how high the specific pressure and how much the material flows under the strain, the general appearance of the compressed surface does not change and metallic contact is obtained only through a small fraction of the crushed surface. Convincing proof of this seemingly improbable phenomenon is given by the following experiment:

Two contact surfaces shown in Fig. 11 (a) and (b) were filed smooth, so that the ridges and scratches caused by the tool pointed in one direction only,

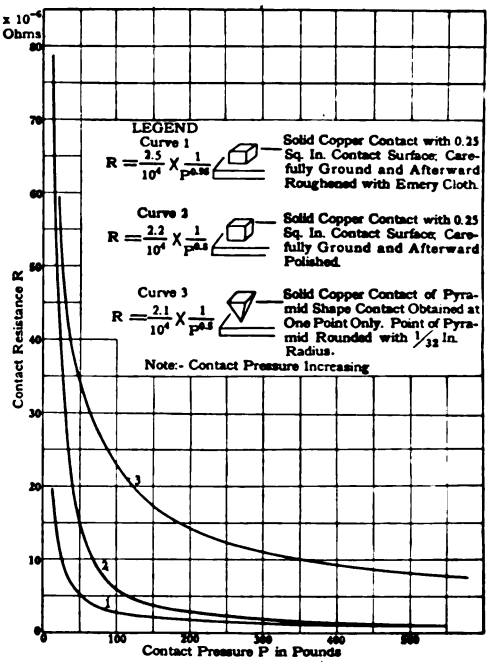


FIG. 9

and were less than 0.0001 inch high. The contacts were then put together with the surface ridges at right angles and compressed with 6000 lbs. This caused the small contact to penetrate about 0.010 inch into the surface of the large contact.

Referring to the photo-micrographs of Fig. 12 (a) and (b), which show the structure of the compressed surfaces 100 times enlarged, it will be noted that the more or less regular tool scratches are hori-

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zontal in (a) and vertical in (b). The irregular marks running at the right angles to them, are the result of compression and are caused by the projecting ridges penetrating into the respective surfaces. They are the only points where the two surface actually make contact and seem to constitute but a very small percentage of the crushed surface, as shown very clearly in the two photomicrographs.

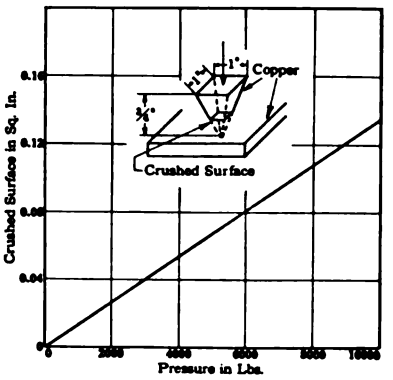


FIG. 10—VARIATION OF CRUSHED CONTACT SURFACE AND PRESSURE

Strange as this fact may be, it is not very difficut to explain it. Consider, for instance Fig. 13, showing the contacts put together with the tool scratches at right angles, as in the above test. The two surfaces are shown before and after the compression and illustrate the deformation of the individual ridges as well as the total flow of the whole surface. The dimensions included in Fig. 13 are obtained from tests made with contacts of Fig. 11 (a) and (b).

Assuming that the upper ridge touches one of the projections of the lower contact on a surface $y^2$, it is obvious that the pressure exerted on this surface compresses not only the crystals directly underneath, but affects also the adjacent material. Hence, if the crystals underneath the surface $y^2$ are pressed down, those surrounding them will support them and, if the pressure is high enough, will be pulled down too, although not quite to the same extent. The farther the crystals are away from the contact surface $y^2$, the less they will support and follow the general down-

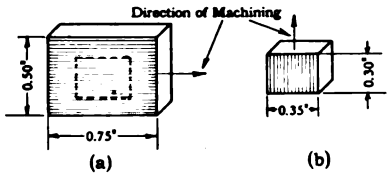


FIG. 11—CONTACTS PREPARED FOR A CONTACT-AREA TEST

ward movement. Thus the whole surface is gradually pressed down, although there are only one or a few compression centers. At maximum compression the contact surface $y^2$ may have increased to $y_1^2$ plus $y_2^2$, which is still but a small fraction of the total crushed surface.

## CONCLUSIONS

The theory of the contact resistance, as outlined in this paper, is based on the assumption that the so-called contact resistance is nothing but the ohmic resistance of microscopic projections or points which actually make up the contact surface. However carefully the surfaces are ground and lined up, the actual contact is obtained at one or several points only, depending upon the flexibility of the material. These contact points, or pyramids, which carry all the current, are of a certain length and consequently have a definite ohmic resistance.

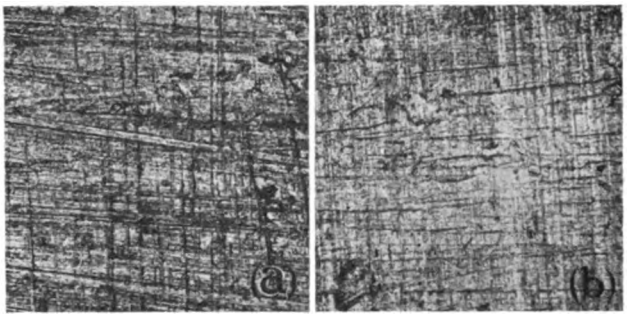


FIG. 12—PHOTOMICROGRAPHS OF CONTACTS OF FIG. 11 AFTER TEST

On these assumptions the contact resistance depends upon:

1—*Contact Pressure,* which controls the height or length of the contact projections or pyramids through crushing, until their flattened surface is large enough to resist the contact pressure.

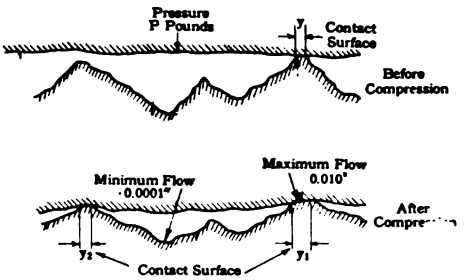


FIG. 13—DIAGRAMMATIC REPRESENTATION OF CONTACT POINTS

2—*Specific Resisting of the Material*—From the foregoing it follows that practically all contact resistance occurs right at the contact surface. The contact resistance, therefore, is a function of the specific resistance of the surface material, or, assuming clean contacts, it is proportional to the specific resistance of the contact material.

3—*Crushing Strength of the Material*—The softer the material, the more the contact pyramids are flattened and their number increased at a given contact pressure. A softer material consequently will give a lower contact resistance than a hard one.

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# Mechanical Features for Motors and Generators for Gas-Electric Buses*

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THE use of an electric generator and motor as a transmission for the autobus has demonstrated that the electric transmission has several distinct advantages over the usual mechanical form. Principal among these advantages are the smoothness of operation, especially during acceleration; simplified and easier duties for the driver; and the resultant reduction of strains in nearly all parts of the vehicle.

The employment of a generator to utilize the engine power and an entirely separate motor to use the electrical power from the generator, has often led to the suggestion that the two machines be combined into one unit using the same frame, pole pieces and field coils for both generator and motor. Nearly all gas-electric buses in service today, however, use a generator and one or two separate motors, the principal reasons being:—

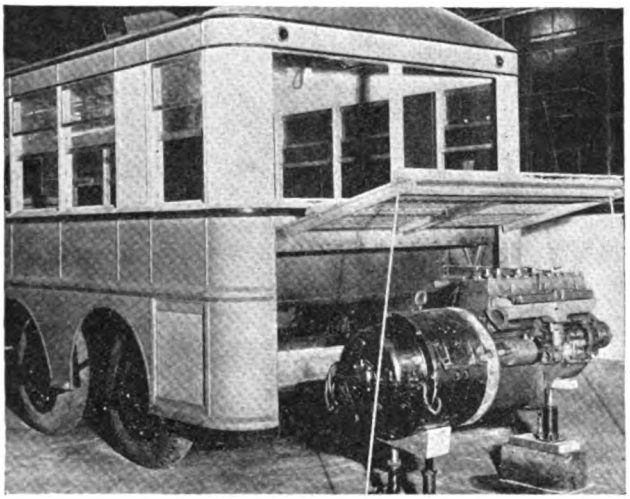

FIG. 1—THE POWER-PLANT UNIT OF A MODERN GAS-ELECTRIC COACH
Showing simplicity and ease of mounting in a unique position.

1—The torque requirements of the generator and motor are widely different. This makes it magnetically difficult to adapt the two rotors to a single field structure.

2—Mechanical complexities arise when two rotors are placed in a single frame unit.

3—Greater latitude in bus arrangement is allowed when the only physical connection between generator and motor is a pair of electric cables. The motor is essentially related to the wheels and the generator to the engine.

## GENERATOR MOUNTING

The general shape of the generator depends on the method of its connection to the engine and its position in the bus. The most satisfactory mechanical connection between generator and engine requires accurate alignment between the two. Fig. 1 illustrates a generator which is bolted solidly to the engine through an adapter casting. The alignment of the generator armature shaft with the engine crank-shaft is necessarily accurate because it is produced entirely by bored or turned fits. The generator has but one bearing, the engine end of the armature shaft being supported in a bushing in the end of the crank-shaft. A flexible, disc coupling forms the actual power connection between the armature shaft and crank-shaft. This unit power plant can be removed from the bus very easily, especially when located in the unique position shown in Fig. 1 across the rear end of the bus.

A generator and engine mounted on a structural steel sub-frame and connected by means of a flexible disc coupling is shown in Fig. 2. This power plant is located in the bus at the conventional engine position, but can be removed more easily than the usual engine. The side members of the sub-frame act as slide rails resting against the corresponding supporting members of the chassis frame.

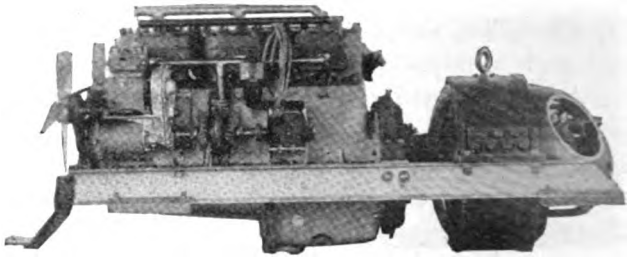

FIG. 2—ENGINE AND GENERATOR MOUNTED AS A UNIT ON A SUB-FRAME

The generator shown in Fig. 3 is particularly well adapted for mounting directly behind the usual engine position without necessarily being in accurate alignment with the engine crank-shaft. An adapter bolted to the engine, supports one end of the generator at two points, as shown in Fig. 3, one on each side of the generator at the fan end. The commutator end is clamped at the cylindrical surface against a cross member of the chassis. The generator may be lowered from its position in the bus by taking out the two supporting bolts and unbolting the semi-circular clamp. The engine power is transmitted to the generator through two flexible couplings, one at each end of a small diameter shaft which passes through the center of the hollow generator armature shaft. This arrangement is practically equivalent to connecting the engine to the generator by a propeller shaft and two universal joints yet it allows the generator to be very close to the engine so that there will be little interference

*The electrical characteristics of motors and generators used on gas-electric buses are described in an article entitled "Characteristics of Generators and Motors for Gas-Electric Traction," in the July 1926 issue of THE ELECTRIC JOURNAL.

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with the bus floor just behind the dash board. The shape of the generator is designed to suit this location. The relatively small diameter permits a minimum of floor interference as well as the necessary clearance between the generator and the ground.

### MOTOR MOUNTING

The fact that the motor (or motors) is mechanically independent of the engine allows considerable

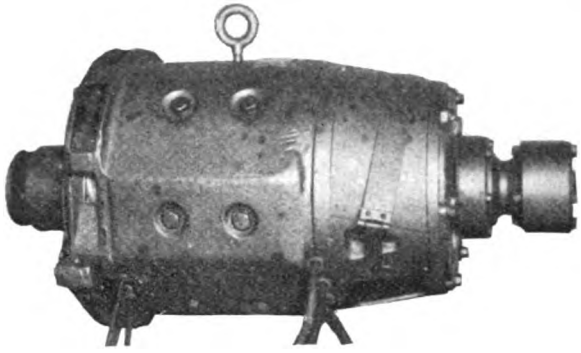

FIG. 3—A GENERATOR WITH A HOLLOW ARMATURE SHAFT AND CONCENTRIC DRIVE SHAFT

Coupling from engine passes through the armature shaft from the left and connects to the armature shaft itself inside the housing at the extreme right.

freedom in its location. The factors determining its position are the method of gearing to the axle and the shape of the chassis or truck.

A motor arranged to be supported from two cross members of the bus chassis is shown in Fig. 4. The shaft extension end faces the rear axle and is bolted up to one bus cross member through the two support lugs, one on each side of the shaft. The other end

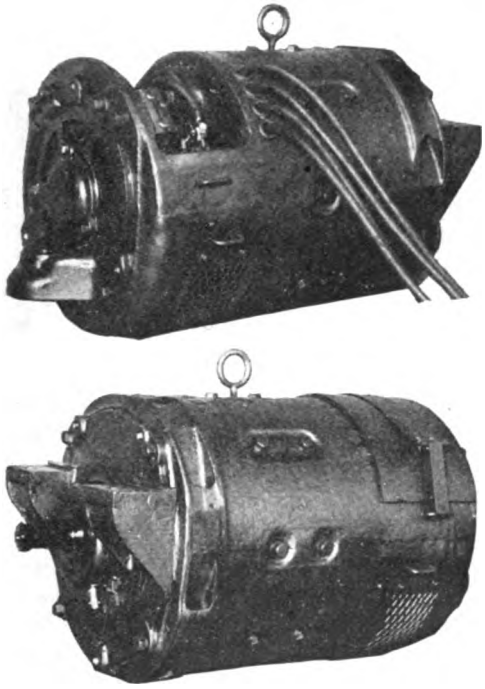

FIG. 4—FRONT AND REAR VIEWS OF A MOTOR ADAPTED FOR END MOUNTING

is supported from a second cross member by a single bolt through the lug below the bearing. Two motors of this type are placed side by side, each driving one rear wheel through a drive shaft, two universals, and a worm gear reduction. This type of drive eliminates the differential and allows greater ground clearance under the motors than would exist if a single motor of twice the capacity were used with the same height of bus floor.

A single motor may be used if the bus floor is raised slightly. Single motor drive has several points of superiority over the double motor drive since it permits the use of a standard mechanical-drive type of rear axle, reduces the number of pieces of apparatus on the bus and has better weight and electrical efficiencies than the two smaller motors.

Another method of using a standard rear axle is to mount two small diameter motors in tandem, as shown in Fig. 5. This requires a shaft extension on both ends of one of the motors and a coupling between the two. Fig. 6 illustrates the motor used for this

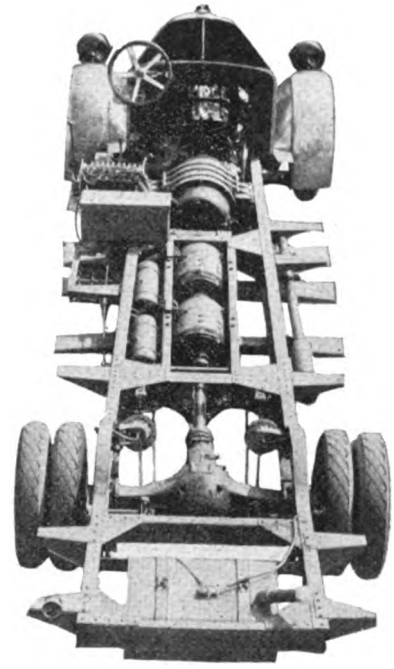

FIG. 5—A BUS CHASSIS WITH TWO TANDEM MOUNTED MOTORS

type of drive. It will be noted that the mounting feet are placed at the sides of the frame in this case.

Another type of drive, developed by the Versare Corporation for their eight-wheel gas-electric coach, is shown in Fig. 7. Two of these bogie trucks are used under each coach, the outstanding advantages of their use being the short turning radius possible with a coach of considerable length and the reduced wheel load for a given total weight. The motors are provided with trunnions and are suspended on links that are free to oscillate on trunnion brackets fastened to the longitudinal channels forming a part of the bogie frame. A spherical casing, one end of which is rigidly bolted to the motor housing and the other end rigidly fastened to the axle beam, encloses a single universal joint, and also acts as a motor support.

### DETAILS OF CONSTRUCTION

Light weight is an essential in all bus equipment, and is obtained in the motor and generator by using

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high strength aluminum castings where steel or iron is not needed as a part of the magnetic circuit. The use of asbestos and mica insulation permitting higher temperatures, a highly efficient uni-directional ventilating fan on the armature shaft, and relatively high peripheral operating speeds are additional factors for obtaining a high horse-power rating per unit weight of machine.

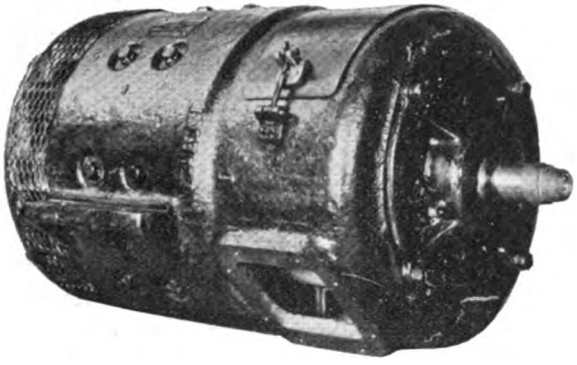

FIG. 6—A MOTOR ADAPTED FOR SIDE MOUNTING

A special scheme of ventilating baffles, shown in Fig. 8, is used which prevents the ventilating air from coming in contact with the commutator and brushes. This keeps dust and wheel wash spray away from these current-carrying parts, and is an important factor in obtaining long life for the brushholders, carbon brushes and commutator.

The armature bearings are of the ball or roller type. Long life is obtained by using bearings suitable for the loads and speeds encountered, and by the use of bearing enclosures which will keep the lubricant in and dust out.

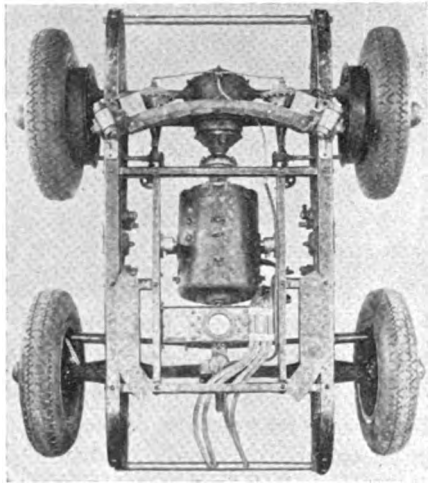

FIG. 7—BOGIE TRUCK FOR EIGHT WHEEL GAS-ELECTRIC COACH SHOWING MOTOR MOUNTING

Quietness of operation of both motor and generator is necessary to be in keeping with the other features of smooth operation of the gas-electric bus. Special attention must be given this point due to the relatively high speed of the motor armature and the rapidly changing speed of the generator armature each time the foot throttle is depressed. Brush noise is minimized by special brushholders with inclined carbons; fan noise, by the correct shaping of fan and air outlets; and magnetic noise, by the use of skewed armature slots and proper proportioning of all parts of the magnetic circuit subject to flux variations.

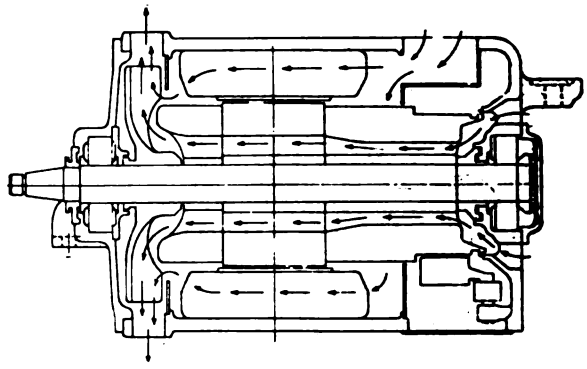

FIG. 8—SCHEME OF VENTILATION FOR BUS MOTOR

The armatures are made safe for the high peripheral speeds encountered by means of special banding and commutator construction and accurate dynamic balance. Fig. 9 illustrates a typical armature construction.

Recent developments made by bus builders indicate that the general shape and arrangement of the future buses built for mass transportation are to be considerably changed, tending toward the form of a street car with pneumatic tired wheels, and placing of the engine elsewhere than at the front of the bus. The gas-electric type of drive will, no doubt, be a factor in working out the most suitable bus arrangement due to the greater freedom of location of the engine than in the mechanical drive. The use of the electric transmission with its numerous points of superiority also seems to be in keeping with the other advances in the bus building art.

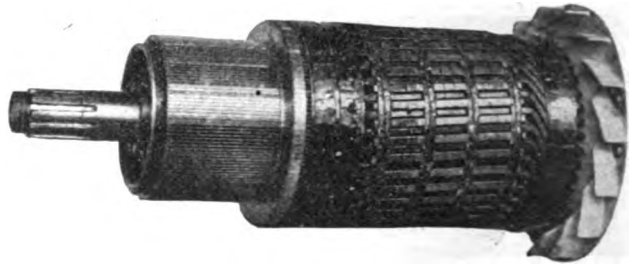

FIG. 9—THE ARMATURE OF A BUS GENERATOR

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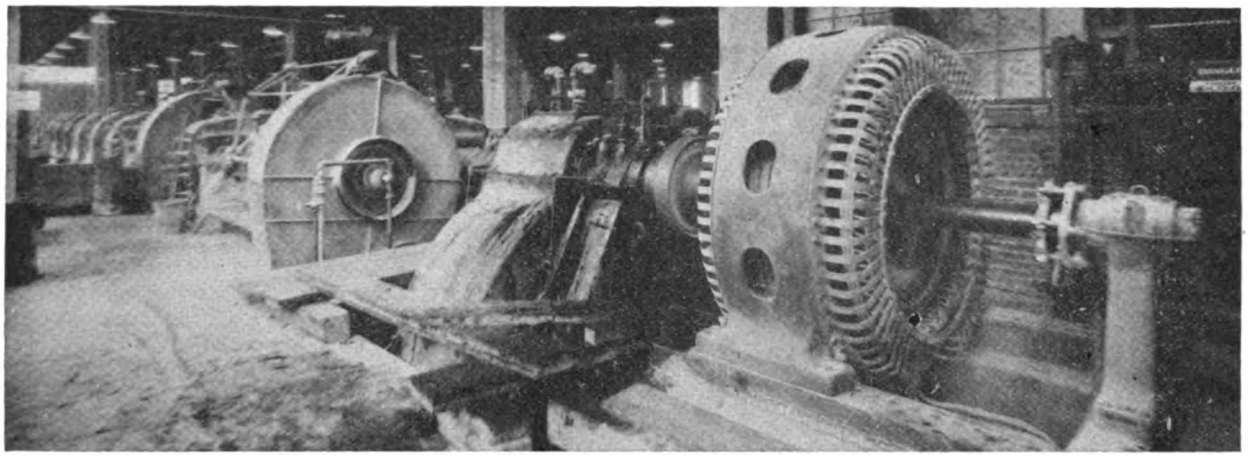
A 700 HP, 600 R. P. M. SYNCHRONOUS MOTOR DRIVING A LINE SHAFT THROUGH A VERTICAL REDUCTION GEAR



# Industrial Motor Applications

## With Especial Reference to The Rubber Industry

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Electrical Engineer, Akron Div.,
The Philadelphia Rubber Works Co.

RUBBER is a tough gum requiring heavy machinery and much power for its working. The drives are usually electrical. Calenders, tubing machines and Banbury mixers are usually individually driven. While the first two are commonly provided with direct-current motors, because of the necessity for speed variation, the tendency is to power Banbury mixers with synchronous motors rather than the slip-ring type. This is likewise true with mills which, except in the case of the quite small plant, are grouped several on one drive.

The low power-factor due to the general use of induction motors has been known, and the desirability of correction realized for some time. The increasing amount of electric power purchased, together with the penalizing of low power-factor in power contracts have made correction an economic necessity. This has led to the development of qualities in the synchronous motor which it previously had not possessed. At first it was usable only as a condenser, or to drive easily started apparatus like motor-generator sets; in fact, on some of the earlier installations, it was necessary to bring it up to speed with a small special starting motor, and then to synchronize it with the line. In such cases, it was applied to mill line drives just as were the slip-ring motors preceding it, a clutch-brake permitting the motor to start light, after which the load was picked up by energizing the clutch. A satisfactory safety stop was secured by opening the clutch and applying the brake to the mill drive. Several forms of mechanical clutch-brakes were used for this purpose, though probably the magnetic type was in most general use, and was most successful.

The difficulty of keeping a drive including a magnetic clutch brake in satisfactory alignment, and the demand for something better, led to the coupling of the motor directly to the load, and the application of dynamic-braking as a safety stop. This required sufficient starting and pull-in torques to bring the drive up to speed light, and manufacturers more recently have found themselves able to do even better than this—to design synchronous motors with torques high enough to start and pull-in normal loads. This, like dynamic-braking, is a distinct advance, as it ends costly production delays caused by the necessity of opening up a line of mills and cutting out the rubber in them, in case of accidental stopping while loaded.

### LINE VOLTAGE STARTING

The starting of squirrel-cage and synchronous motors of all sizes above five horse-power on a reduced voltage, switching to line-voltage when practically up to speed, has long been the accepted method. This starting voltage was sometimes secured through resistances, impedance coils or, most generally, through autotransformer starters. There were several reasons for this. It was believed that full-voltage starting would damage the motor and also the machinery driven. Earlier power plants, whether public or private, were small, and the high kv-a drawn during across the line starting, would in the former case seriously affect voltage regulation, or in the latter, cause no-voltage releases on other drives to trip out, or would even overload the generator. This led to the adoption of rules by associations of public utilities, which actually set a maximum limit on the starting

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kv-a each customer might draw, but in effect required the use of reduced voltage-starters.

This attitude prevailed long after power plants had grown in size to the point where this requirement was no longer needed; and continues today to an extent which is surprising when the economies of full-voltage starting are considered.

The many types of self or switch-start motors which have been developed, are strongest evidence of the desire to get away from the older type of starting equipment and its troubles. The latest of these are the double-deck and like designs. While there are undoubtedly some applications where such motors will fit in as well or better than the standard, or general utility squirrel-cage type, it is the writer's conviction, after due investigation and consideration, that such applications are few and unusual, and that careful study should be given each case before deciding to

TABLE I—OPERATING CHARACTERISTICS OF RUBBER MILL MOTORS

| Hp | R. p. m. | P-F | Percent Starting Kv-a | Percent Torques | | | Percent Efficiencies | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Starting | Pull In | Pull Out | 1 | ¾ | ½ Load |
| 300 | 600 | 0.70 | 415 | 230 | 109 | 260 | 91.88 | 92.08 | 91.05 |
| 400 | 600 | 0.80 | 360 | 195 | 80 | 243 | 93. | 93.2 | 92.4 |
| 500 | 93.8 | 0.80 | 550 | 125 | 90 | | 92. | | |
| 500 | 97.3 | 0.80 | 475 | 130 | 100 | | 93.2 | | |
| 600 | 81.8 | 1.00 | 540 | 120 | 85 | 200 | 91.9 | 91.5 | 90. |
| 600 | 81.8 | 1.00 | 440 | 100 | 70 | 200 | 91.9 | 91.5 | 90. |
| 600 | 100. | | 450 | 140 | 100 | 260 | 92. | | |
| 700 | 600. | 0.80 | 310 | 129 | 79 | 350 | 94.8 | 94.4 | 93. |
| 700 | 81.8 | 1.00 | 268 | 100 | 80 | 200 | 93.1 | 92.1 | 90. |
| 700 | 81.8 | 1.00 | 281 | 105 | 80 | 250 | 92.5 | 91.4 | 89. |
| 700 | 81.8 | 1.00 | 450 | 105 | 65 | 240 | 93.5 | 92.4 | 90. |
| 700 | 81.8 | 1.00 | 277 | 104 | 80 | | 93.4 | 92.5 | 91.1 |

install any of these types in preference to the customary standard motor. It must be considered that in some of the design compromises through which low starting currents are secured, with usable starting torques, running power-factors suffer seriously.

Excepting some applications involving high inertia, such as flywheels, or parts of considerable $WR^2$, revolving at high speeds, which may require smooth acceleration over a long time interval, it has been amply demonstrated that no undue strain is put upon either motor or driven machinery by either full-voltage starting or dynamic-braking. Due to the magnetic stresses caused by the high current in starting, it has been found desirable, with those motors having a long coil-end overhang, to brace these, usually by tying them to a ring.

Many public utilities are now allowing quite large motors to be started full voltage even on their secondary distribution systems, and are making little or no restrictions on their primary systems. It may be of interest to note that one rubber factory, supplied at 22 000 volts by a large utility, is regularly starting a 250 hp, 1800 r.p.m. general utility squirrel-cage motor on full-voltage, as well as a 700 hp, 600 r.p.m. synchronous, and a 400 hp, 450 r.p.m. synchronous motor of an older type, not designed for across-the-line starting. All these are on a 1200 kv-a, transformer bank; the 250 hp drawing 1683 kv-a, or 422 amps., the 700 hp 2100 kv-a, or 571 amps., and the 400 hp, 3988 kv-a, or 1000 amps., and all without trouble of any sort, the voltage "dip" being less than ten percent, and hardly noticeable on the lights. Two 300 hp, 600 r.p.m. synchronous, and a number of 75 hp and smaller squirrel-cage motors, are likewise so started. This factory is replacing reduced-voltage starting with across-line throughout as fast as is economical, and will buy only full-voltage equipment in the future.

This full-voltage starting has proven so successful that a large, new reclaiming plant in Pennsylvania, containing eleven 400 hp synchronous, and a number of 100 hp squirrel-cage, as well as smaller motors, is so equipped. There are no slip-ring, self-start, double-deck, direct-current, or other special type of motors in this plant, all being either synchronous or general-utility squirrel-cage.

The gains by line-voltage starting are manifold and manifest. The first cost is greatly lessened, being roughly in the ratio of 2 to 1, though varying with size and voltage. This is more marked with automatic as compared with manual controls. Another gain is that the simple line-voltage magnetic contactor, giving push-button operation, being inexpensive, permits doing away with manual operation at no, or slight, increased cost. The greatest gain, however, is in lowered maintenance, experience having shown that contact replacement is seldom required, while compensator-starter contacts burn badly, and autocoils burn out quite often. Line contactor parts are easily accessible, while compensators, with their compact construction, oil tanks and tripled number of contacts, are much more difficult to maintain. This reduction in maintenance shows up particularly when starting and stopping is frequent.

The high starting-current inrush with across-the-line starting, which ranges from three times normal for a slow-speed synchronous, to eight or ten times normal for a high-speed squirrel-cage motor, tended to trip the customary oil dashpot form of overload relay, when used with full-voltage starting, unless by-passed or cut out until the current had decreased. Hence a thermal, and particularly a thermostatic form was developed, which has proven excellent. It is not only satisfactory for this application, but is found preferable for most overload protection since, because it responds to heating effect rather than to current, it follows the actual heat condition of the motor more closely. It is likewise free from the troubles inherent to a dashpot—the throwing out of the oil, sticking due to dirt, oil gumming, or pot warping, and inability to secure a sufficiently long time delay. Experience with some two hundred relays of this type, over five and six years, has shown it to give decidedly better service than any other.

The older designs of synchronous motors required starting kv-a inrush undesirably high in many cases for full-voltage starting. It has been found possible

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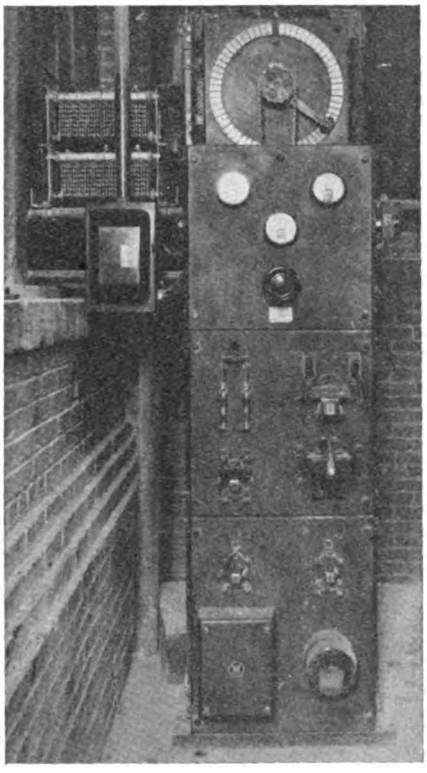
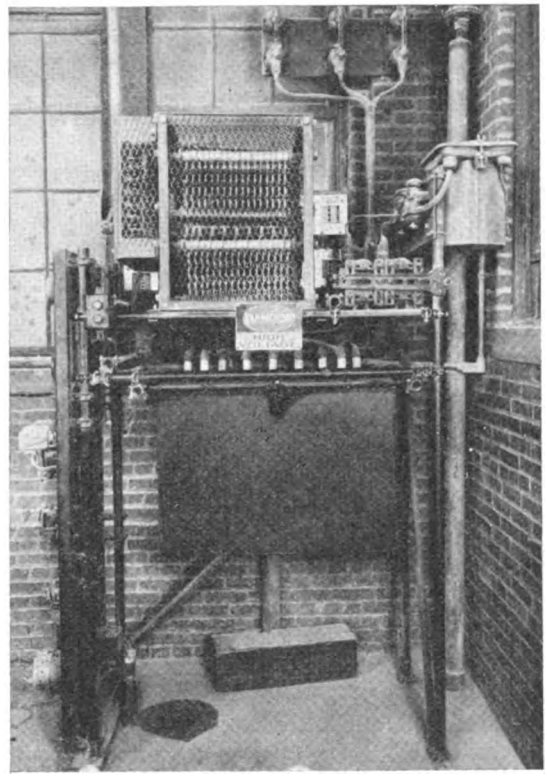
to reduce this, retaining the required torques, by changes in the amortisseur winding, sometimes in the metals used and by utilizing the field circuit, either by employing a high resistance during starting, or, as is done by some manufacturers, by starting with the field circuit open.

What is being accomplished along this line is shown in the list in Table I of some motors in the rubber industry, either recently offered, under order or actually in service: It is interesting to note that in the case of the 700 hp motor referred to, it would have been impossible to secure the required starting torque on reduced voltage without greatly increasing the starting kv-a above that required for full-voltage starting.



A FRONT VIEW OF THE FULL-VOLTAGE DYNAMIC-BRAKING STARTER FOR THE 700 HP VERTICAL REDUCTION GEAR MOTOR



A SIDE VIEW OF THE STARTER SHOWN ON THE LEFT

Because of these developments, and because the synchronous motor is much cheaper than the slip-ring (and the squirrel-cage as well, in the larger, slow-speed sizes), the tendency has been to apply it nearly everywhere, even to loads previously thought to require a high-slip, squirrel-cage motor with flywheels. The hog, or chopper, with many momentary high peaks, as well as the Banbury mixer, illustrate this type of load. The use of a synchronous motor, with satisfactory maximum torque characteristics, has been quite satisfactory under these and similar conditions.

### SPECIFYING MOTOR SIZES

Good engineering and good judgment must be used to avoid over-investment, while at the same time adequately powering the drive and insuring minimum trouble and maintenance. There is a tendency to be on the safe side—to specify a motor which is too large rather than too small; and of the two evils undoubtedly over-motoring is to be preferred. Specifying a synchronous motor of reasonable leading power-factor, making sure that torques are ample, is one good way out of this dilemma. Synchronous motor efficiency curves can be made flat, falling only slightly at three-quarters or half load, while the induction motor, never so good as the synchronous, may drop five points at half-load. This is an important consideration in motor choice, since a well selected motor for mill line drive may be called upon for 150 percent of its rating over considerable periods, while usually it will be carrying around 70 percent of its rating, this wide range being due to the differing nature of the stocks handled. The induction motor power-factor, even if good at rating, will drop seriously, as much as 20 points, at three-quarters and half-load, while that of the synchronous motor improves. Such a motor, for example one rated 700 hp at 80 percent, has a capacity of 875 hp, at unity power-factor, with the same heating.

### DYNAMIC BRAKING AND PLUGGING

Dynamic-braking, as applied to synchronous motors, is a development of the last few years. It consists simply in disconnecting the motor from the line and shorting its terminals through suitable resistances, the field being maintained. The kinetic energy of the motor and drive is thus compelled to do work, which is dissipated in the resistances. It is possible by this means to come to a stop within 30 cycles, or less, from the time of pulling the safety bar at the mill, which,

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if the running speed is 600 r.p.m., means less than five revolutions, or one-half second.

Plugging, which is also sometimes used as a safety stop, consists in reversing the line connections, and disconnecting the motor when brought to a full stop. It is, of course, applicable as well to squirrel-cage and slip-ring motors, whereas dynamic-braking is limited to the synchronous. Plugging fails as a safety stop, should the unlikely happen, a power failure at the critical moment of accident.

It is self-evident that all circuits involved in safety stopping should normally be closed, and any break or accidental opening, should, as well as the intended manipulation of the mill safety bar, result in a safety stop. This requires a dynamic-braking (or plugging) contactor functioning either by gravity or spring-impulsion. The converse-safety stopping obtained through the closing of a contactor against gravity or spring, its operating coil being energized either directly or through a relay actuated by the cradle switch, should be shunned. It is a common thing for wires to break, particularly at the point of clamping by the binding screw, screws frequently loosen, dirt on a switch or relay contact sometimes prevents current flow, and actuating coils have been known to burn out.

The development of a gravity-actuated, double-throw contactor for dynamic-braking (or plugging) has likewise greatly simplified the remainder of the control.

It is difficult to realize how simple a complete full-voltage dynamic-braking control can thus be made, yet possess every possible feature of protection and safety. Simplicity means fewer delicate relays, contacts and interlocks to keep clean and in order; it means locating trouble more easily; and fewer and shorter interruption to production. Controls must usually go in the same room as the motor, and quite frequently both must be installed in the open mill room, and subject to all the dirt conditions which exist there. This particular form of control is unusually economical of floor space, an important factor when every square foot must earn its way.

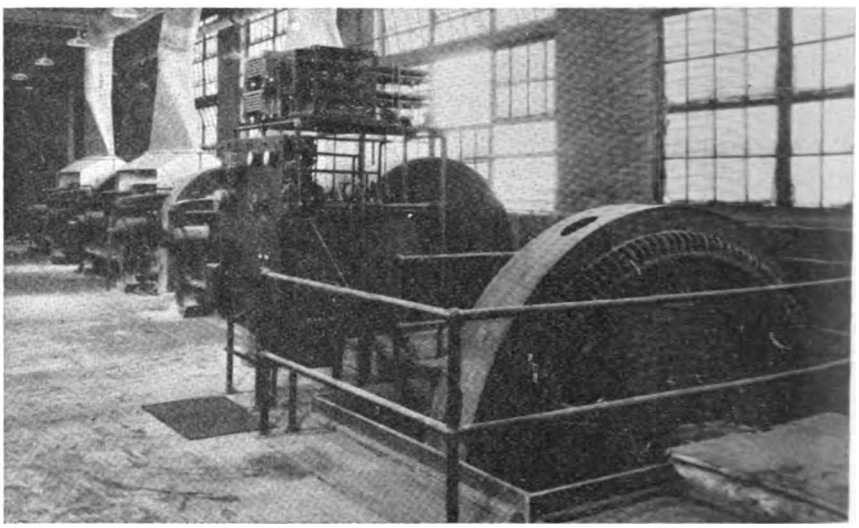
### METHODS OF CONNECTING MOTOR TO LOAD

Though the tendency is toward the installation of slow-speed motors direct-connected to the line-shaft, this is not always the most economical plan, and many drives are being installed, consisting of high-speed motors and reduction gearing. Such gearing, as now manufactured, is highly efficient and long-lived. A 600 r.p.m. motor is also considerably more efficient than the same rating at 82 r.p.m., as well as much lower in cost. Less floor space will likewise be required by this combination, so that, with the correct evaluation of all cost factors, the direct-connected slow-speed unit may prove the less economical.

A vertical reduction gear, the pinion being directly above the gear, instead of to one side, as in the older form, has proven advantageous. The motor is thus kept above the floor, easily accessible for cleaning, inspection and repair. It is also out of the old time pit, which is the receptacle for the sweepings and trash, and is frequently flooded, when a drain stops up or water line bursts.

### CIRCUIT BREAKERS INSTEAD OF FUSES

A step in advance which some newer rubber factories have made, is to eliminate the fuse in power circuits. This has been done by grouping several motors, with their starting contactors on one circuit breaker, of an enclosed type having inverse-time-elements permitting the high starting current inrush while giving adequate protection against conditions not cared for by the overload relay on the individual control. It is frequently possible to group as many as eight or ten motors on one circuit breaker, depending upon the size and drive characteristics. The saving in maintenance costs, as well as the production savings due to the ending of delays caused by waiting for an electrician to replace fuses, is considerable.



A 600 HP, 120 R.P.M. SYNCHRONOUS MOTOR DIRECT CONNECTED TO THE MILLS
The complete control equipment is located to the left of the motor.

The Pennsylvania reclaiming plant referred to, which is also one of those without fuses, likewise is equipped throughout (except in the 400 hp size) with roller-bearing motors. The use of antifriction bearings is increasingly general in the rubber industry, many plants buying motors only so fitted. Antifriction bearings are being more widely used on other machinery as well, a 3500 gal. per min. centrifugal pump at 1800 r.p.m. being mounted on ball bearings, as well as the 250 hp squirrel-cage motor driving it. The field of application is being broadened, so that the industry expects soon to see antifriction bearings on

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heavy mill line shafts, as well as on roll journals. Their use is commencing on large reduction gears.

It has been the writer's experience that maintenance charges are markedly decreased through the use of antifriction bearings. Failures, with consequent production losses, are much fewer, replacement, when required, is cheaper and quicker, much less lubricant is used and, most important of all, where monthly or weekly oiling was previously required, attention at intervals of six months or three months is all that is required for ball or roller bearings, so that the maintenance force can be considerably reduced. Perhaps as important an advantage as any is the elimination of rewinds necessary, because of burn-outs due to oil-soaked insulation.

The rubber industry is at the forefront of engineering progress, and in its endeavors to supply its product at the lowest possible cost, has found full-voltage starting of motors, with consequent simplicity and ruggedness of control, one factor contributing to that end. Another has been the elimination of the clutch-brake, made possible by dynamic-braking and plugging as safety-stops. The use of the synchronous motor, as well as fitting in with both full-voltage starting and dynamic-braking safety-stop, has also resulted in economies, through power-factor correction and inherent efficiencies over the wide range of loads experienced. Antifriction bearings are greatly reducing maintenance problems, and circuit breakers instead of fuses are proving highly profitable.

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# Graphical Flux Mapping

## V—Direct Current Motors and Generators

J. F. CALVERT and A. M. HARRISON

A SALIENT-POLE machine was shown in the first figure of the first article of this series* to illustrate the general principles used in plotting all the magnetic fields which have been shown. However, no explanation was given to indicate the easiest means for drawing this particular flux map.

A brief consideration of the main magnetic circuit, such as that in Fig. 42, will show that there is symmetry within each pole pitch. The adjacent coil sides of adjacent poles carry current in the same direction. The ampere-turn lines must emanate from one or more centers in conductors carrying current in one direction, and converge on corresponding m. m. f. centers in conductors carrying current in the reverse direction. This is necessary if the flux is to link the current. Also, these ampere turn lines cannot cross. Consequently, the ampere turn lines must start from the winding on one side of a pole, pass through the gap and close in on the other side of the pole in the same field coil. The flux must pass perpendicularly across the center line between poles.

It is simplest to start the drawing in the air-gap. Assuming no saturation in the iron parts, the entire magneto-motive force per pole is acting in this space. The flux must pass almost radially across the gap and the ampere turn or orthogonal lines are circumferential in this space. Suitable divisions of flux and ampere turns can be chosen, such that the ampere turn lines cut curvilinear squares from the flux tubes. Each square will represent a reluctance of one per unit of depth perpendicular to the sheet, and each flux tube will represent an equal number of lines.

The methods of plotting around external corners (as at the pole tips) and into internal corners (as at the center line between poles) have been explained in the first article.

The mapping is then projected, by the method of drawing curvilinear squares, into the space between the tips of the main pole and the commutating pole. Thus far, it has not been necessary to consider

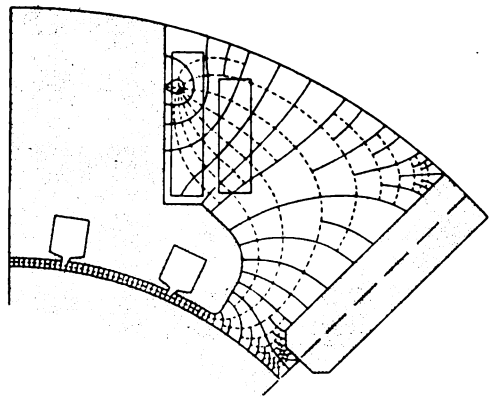

FIG. 42—AIR-GAP AND INTERPOLAR FLUX FOR A FOUR-POLE DIRECT-CURRENT GENERATOR WITH ONLY THE MAIN FIELD WINDING EXCITED

This machine is supplied with both a commutating-pole winding and a compensating winding, the latter distributed in slots along the face of the main pole. As it was assumed in making this drawing that only the main field winding was excited, these other considerations enter only insofar as the configurations of the iron surface have been altered to accommodate these other windings.

the shape or location of the main pole winding except to see that all the orthogonal lines proceed toward the field winding within each pole pitch, so that they may converge on centers as has already been described above. This may be continued until a conductor is reached. Then it becomes necessary to make a preliminary estimate of the location of the m. m. f. center, and to project the ampere-turn lines toward this center, so that they divide the area of the

*March, 1928 issue.

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copper into equal parts (since it can be seen at the gap that equal magnetomotive forces are effective between them); and so that these ampere turn lines and flux lines fulfill the fundamental relations between reluctance and ampere turns (as described in detail in the first article). The method is one of trial and error, and must be repeated until accuracy is attained. Sufficient accuracy for ordinary calculations can be obtained in a very short time; for while conditions in the region around the m. m. f. center are difficult to establish with great accuracy, the densities and the question of interlinkage are only slightly affected by failure to fix precisely the location of the m. m. f. centers. With sufficient care, considerable accuracy can be obtained in all parts of the field. This type of field can be made of use in the determination of field forms, leakage coefficients, and saturation curves.

To make a sketch like the one shown in Fig. 43, the start can best be made at the air-gap. If the interpolar field has been drawn first, the location of the m. m. f. center is known fairly accurately for both views (though the locus of these centers is not necessarily in a cylindrical plane coaxial with the shaft, yet usually it is nearly so.) As the field is extrapolated from the gap, the iron surfaces near the start of the drawing become less and less the predominating influences. The conductors become an appreciable factor. In this type of drawing it is best to rough in an approximate field in the large air space with a skeleton work of big curvilinear squares (and rectangles when within the copper), and endeavor to close this field approximately. If this is accomplished, it is definitely possible to balance the field and make refinements to increase the accuracy of the whole drawing.

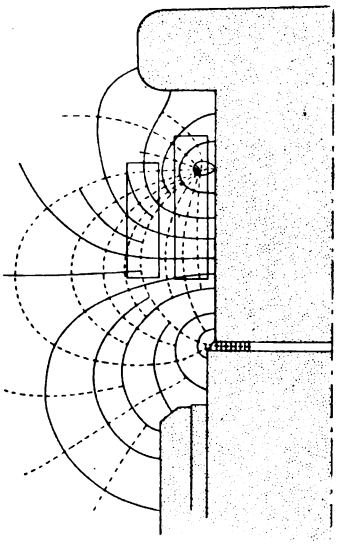

FIG. 43—END ZONE FLUX FOR THE MACHINE SHOWN IN FIG. 42 WITH ONLY THE MAIN FIELD WINDING EXCITED

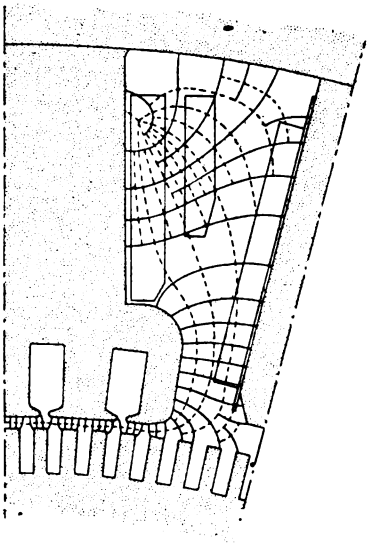

FIG. 44—FLUX DISTRIBUTIONS IN A TWELVE-POLE DIRECT-CURRENT GENERATOR WITH ONLY THE MAIN FIELD WINDING EXCITED

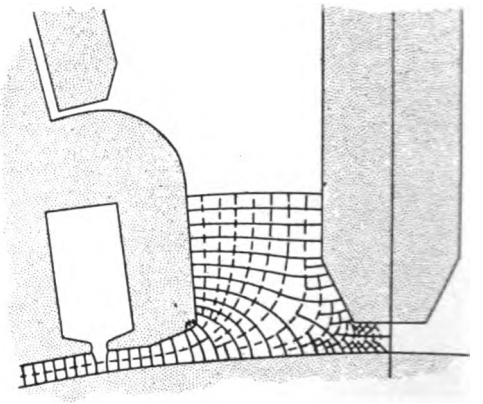

FIG. 45—THE FLUX DISTRIBUTION IN THE COMMUTATING ZONE FOR THE TWELVE POLE MACHINE WITH ONLY THE MAIN FIELD WINDING EXCITED

This drawing is made without determining the flux distribution within the field copper.

As explained in a previous article, the end zone flux, Fig. 43, cannot be drawn accurately. The distribution here is in reality a three dimensional affair. It can be approximated to a certain extent in the centerplane of the field pole, as shown. The section considered is of incremental depth perpendicular to the sheet, and should be wedge-shaped; but, in order to allow the use of this two dimensional method of plotting, the incremential section must be considered of constant depth perpendicular to the sheet. Nevertheless, this type of drawing can be shown to compare rather favorably with a filing or compass picture made in the same space. This has been demonstrated for end zone drawings in previous articles.

In most machines, the interpolar flux is larger than the end flux; and, if accuracy can be attained in the former and a good approximation in the latter, quite reliable data should result.

Figure 44 is similar to 42, but is for a machine with 12 poles. It can be seen that in either of these two drawings, if numbers were placed on the poles and other iron parts near the air-gap, and were so chosen that their differences represented the ampere turns between the surfaces in the directions from the higher toward the lower numbers; then these drawings could be made down to the field conductors without any furthur consideration of the field copper. Therefore, if the air-gap and the commutating zones are the parts of chief interest, Fig. 44 could be drawn as shown in Fig. 45.

If the commutating-pole and compensating windings alone are excited, they form a symmetrical field in each commutating-pole pitch. The ampere-turn lines from the conductors on one side of the pole center line join to centers in the corresponding centers on the other side, as in Fig. 46, and the field in the commutating zone, due to this winding only,

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may be drawn by processes analogous to those just described for the main-pole field.

Similarly, a field for the armature only may be drawn, as shown in Fig. 47. The only difficulty in the latter is that the number of teeth per pair of poles is odd, and considerable precaution must be taken to see that the total flux across the gap in the two directions is equal.

The resultant field when all three windings—the main field, the commutating-pole and compensating

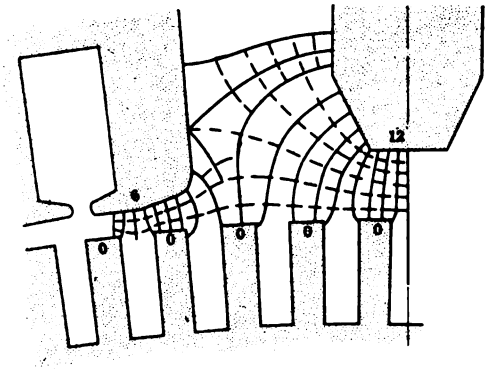

FIG. 46—THE FLUX DISTRIBUTION IN THE COMMUTATING ZONE FOR THE TWELVE-POLE MACHINE WITH ONLY THE COMMUTATING-POLE FIELD AND THE COMPENSATING WINDING EXCITED

winding, and the armature—are carrying currents at the same time is shown in Fig. 48. The same methods of mapping may be used as in the last few drawings, i. e., that of giving numbers to the iron surfaces near the gap, so that the difference in these numbers gives the m. m. fs. existing in the directions from the higher toward the lower numbers. This system has been illustrated in some detail for turbine generators in the previous articles.

There are two possible advantages in mapping the combined field. The first is that if the resultant densities are desired along the armature surface, it is

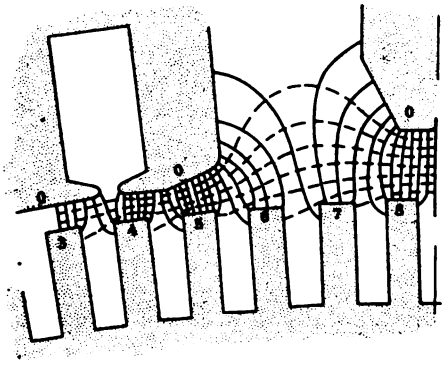

FIG. 47—THE FLUX DISTRIBUTION IN THE TWELVE-POLE MACHINE WITH ONLY THE ARMATURE EXCITED

probably the most accurate, because the values desired are obtained directly; whereas a subtraction of the larger individual fields to obtain the relatively small result may introduce errors from each of the larger drawings and the resulting discrepancy be appreciable. The second advantage is that if correction is to be made for saturation, it can best be accomplished from the resultant field.

Applications of the individual fields have been done very successfully by R. Mayeur*, and methods of considering permeability in a number of different applications in salient pole machines have been shown with great clarity by Th. Lehman.**

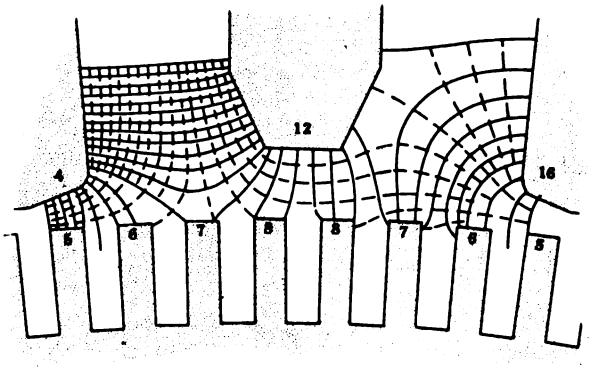

FIG. 48—THE FLUX DISTRIBUTION IN THE TWELVE-POLE MACHINE WITH THE MAIN FIELD WINDING, THE COMMUTATING POLE AND COMPENSATING WINDING, AND THE ARMATURE EXCITED AT ONCE

There is another field which is of considerable importance in certain theories of commutation. Fig. 49 shows the flux distribution due to only one coil while it is undergoing commutation. If this field is used in considering the inductance, some care should be taken to see that this m. m. f. acting in the air in

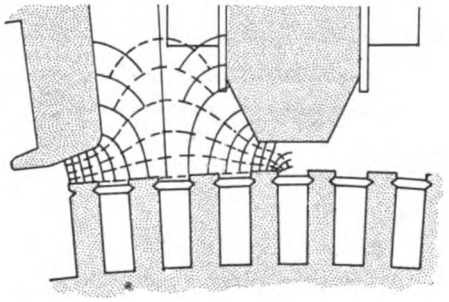

FIG. 49—FLUX DISTRIBUTION IN THE COMMUTATING ZONE FOR THE TWELVE-POLE MACHINE DUE TO ONLY ONE OF THE CONDUCTORS UNDERGOING COMMUTATION

the commutating zone, is not counted twice by including it also in considerations of the total armature flux. This would be an error, though slight.

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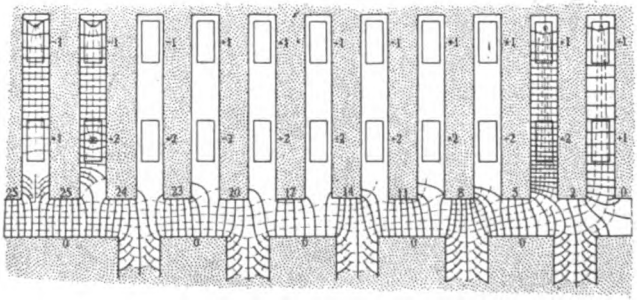
**2—"Determination of Partial and Resulting Magnetic Fields in Saturated Dynamos", by Th. Lehman, *Revue Generalé d'Electicité*, Dec. 24, 1927, pp. 1105-1119.

**3—"The Interpolar Fields of Saturated Magnetic Circuits", by Th. Lehman, *Journal A. I. E. E.*, Dec. 1927, p. 1411.

CORRECTION



The numbers were omitted from Fig. 26 of this series. The correct numbers are as shown here.

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# Effects of Corona in Various Gases on Insulation and Losses

C. F. HILL
Research Engineer,
Westinghouse Electric & Mfg. Co.

WITH the possibility of using various gases and mixtures of gases, other than air, for cooling electrical machines, the question of the life of insulation as affected by corona in the various gases becomes of interest. Tangible proof of what may be expected to take place can be obtained by a setup as follows: a conducting layer is placed inside a glass tube of about one inch diameter and three feet long. Insulation is wound around the outside of the tube and a wire helix around this with a pitch of about one inch. The whole is placed inside a larger glass tube which is arranged so that a gas can be circulated through the system as desired. Electrical leads enter at two points, connecting to the wire helix

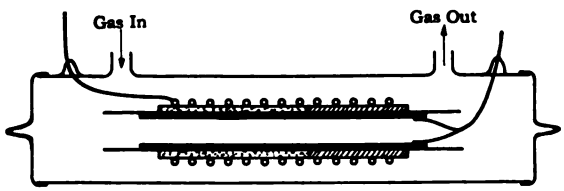


FIG. 1—ARRANGEMENT FOR TESTING INSULATION IN VARIOUS GASES

and to the lining of the inside tube so that high voltage stresses can be placed across the inner tube and insulation. An intense corona then takes place around the helical wire, more or less directly in contact with the insulation samples to be studied or exposed. Fig. 1 shows the apparatus for such a test.

In the presence of air or oxygen, corona forms ozone which in turn rapidly attacks all organic insulations. The first and most noticeable effect is that the organic insulations tend to become hard and brittle, even after a few hours exposure, but such materials will eventually be destroyed if the corona is at all intense. That the effect is completely due to the oxygen can be shown by exposing similar samples to pure hydrogen, $CO_2$ or nitrogen. Over rather long periods of time, insulations retain their mechanical and electrical properties when exposed to corona in these gases, especially in pure hydrogen and nitrogen. It was noticed that the corona in oxygen and air in some recent tests was rather noisy, being accompanied by static discharges near the ends of the electrodes; and apparently there was a larger amount of heat generated than in other gases, i.e., the tube became hotter. As there is little difference between the arc potentials of the various gases, the energy dissipated by the corona could not be expected to cause serious differences in temperature. To check this, the actual watts lost as supplied from the electrical circuit with varying voltages was experimentally obtained for each of several gases and curves representing the results are given in Fig. 2. The energy loss is about of the order expected from the arcing potentials. The difference

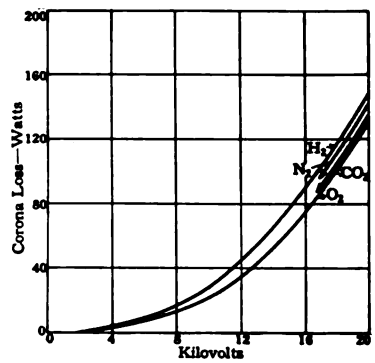


FIG. 2—CORONA LOSS IN VARIOUS GASES

in the heating effect actually obtained may be explained partially by oxidation of the insulations in the presence of the air or oxygen.

It is apparent that the problems of the insulation engineer are made easier by the use of hydrogen, etc., in that the insulation is less affected by other gases than by oxygen.

Some insulation which has been exposed to corona in oxygen and in hydrogen for a few days is shown in Fig. 3. The varnished cloth sample became hard

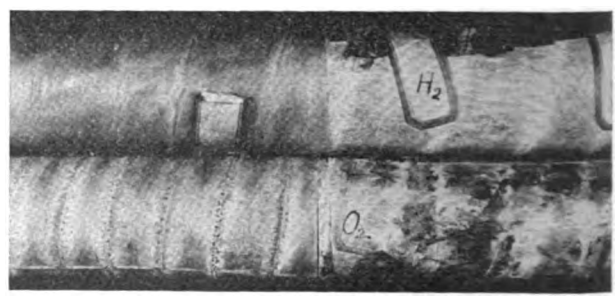


FIG. 3—INSULATIONS AFTER EXPOSURE TO OXYGEN AND TO HYDROGEN

and brittle and much scoured in oxygen, while in hydrogen it was almost as fresh as before the test. In the case of mica pasted to paper (mica folium) and wrapped on the glass tube with the paper side out, the paper was virtually eaten away in the oxygen corona while in the hydrogen corona it was in perfect condition.

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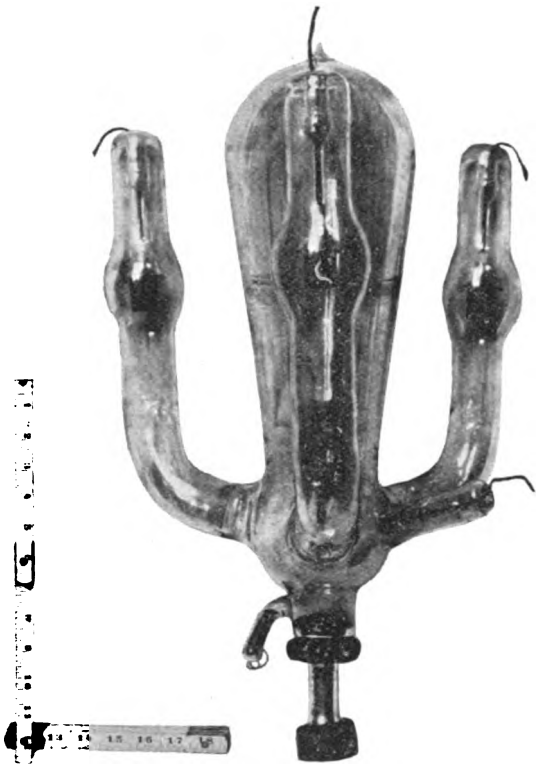

# High-Voltage Mercury-Arc Rectifiers

L. SMEDE
Research Engineer,
Westinghouse Electric & Mfg. Co.

**The unidirectional conductivity of the mercury arc was first investigated by Peter Cooper Hewitt in 1902. Since then small low-voltage rectifiers have been used for battery charging. Quite recently the demand has been met for glass bulb rectifiers which have a larger output, e. g., 150 kw at 600 to 1000 volts. Rectifiers for this type of service can be mounted with their associated transformers, circuit breakers and other apparatus in a small space, and can be made entirely automatic in their operation.**

WITH the development of radio and the need for larger power outputs, attention has been turned to the mercury-arc rectifier as a source of the direct-current power. Rectifiers for radio use are called upon to furnish power of the order of 300 kw or more at from 10 000 to 15 000 volts. In manufacturing apparatus of this type, great care must be exercised in both the mechanical and electrical construction.

The first and foremost consideration is to have an absolutely air-tight glass container fitted with metal lead-in wires. The life of the rectifier is practically governed by the care taken in the manufacture of the container and metal to glass joints, and also by the thoroughness with which the gas is removed from the glass walls and electrodes within the rectifier. The methods by which these results are accomplished are well known in vacuum practice.

Rectifiers must be provided with some form of starting device. A simple form consists of a short side tube containing an electrode, sealed on at the level of the cathode pool and filled with mercury. To start the rectifier a 30 volt battery is connected through a resistance between the cathode and the starter electrode. The rectifier is then tilted slightly and a stream of mercury flows between cathode and starter. Upon the breaking of this stream an arc is formed between the starter and the cathode. The main power supply may then be connected and the starter disconnected.

It is necessary to provide the rectifier with two auxiliary anodes called keep-alives. The purpose of these is to prevent the main arc from being extinguished in case the load current falls to a small value. These anodes can be run as a single-phase rectifier from a low voltage supply and carry from three to five amperes. The energy dissipated in the keep-alive circuit is of the order of 200 watts.

The most important cause of failure of a rectifier is a short-circuit between anodes or between anodes and cathode. Probably the most common reason for such a short-circuit, or backfire, is the presence of foreign gases, due to poor evacuating; but a short-circuit may be due to overloading the rectifier. In the case of high-voltage rectifiers, backfiring can also be caused by too high a mercury vapor pressure. Hence it is important to know just what the limits are at which it is safe to operate a rectifier.

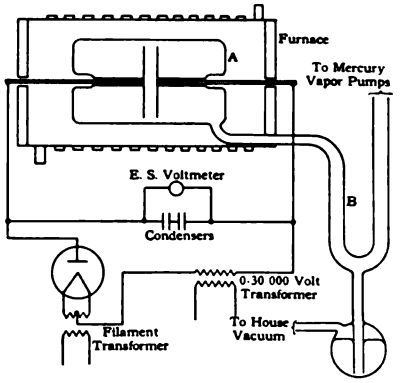


FIG. I—THE ARRANGEMENT USED FOR DETERMINING BREAKDOWN VOLTAGE OF MERCURY VAPOR

In order to determine the breakdown voltage of mercury vapor, the arrangement shown in Fig. 1 was used. The experimental tube *A* was placed in the furnace and heated to various temperatures. The mercury column can be raised in *B* until it comes to a definite height within the furnace and then a breakdown test can be made between the electrodes in *A*. Following the breakdown the mercury can be lowered

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and the tube evacuated so as to remove any gases which may have been liberated during the discharge. Curves were taken with various electrode spacings, the electrodes being made of iron. The results are shown in Figs. 3 and 4.

It was found that the curves taken with electrodes which are close to the glass surface, give a higher breakdown for the same pressure than do tubes in which the electrodes are removed from the glass wall. This is probably due to the collection of charges by the glass wall which hinder the breakdown of the gas. The breakdown voltage can be lowered by introducing either positive or negative ions into the space between the electrodes. However, it is well known that the negative ions are more effective in producing ionization and consequent breakdown than are the positive

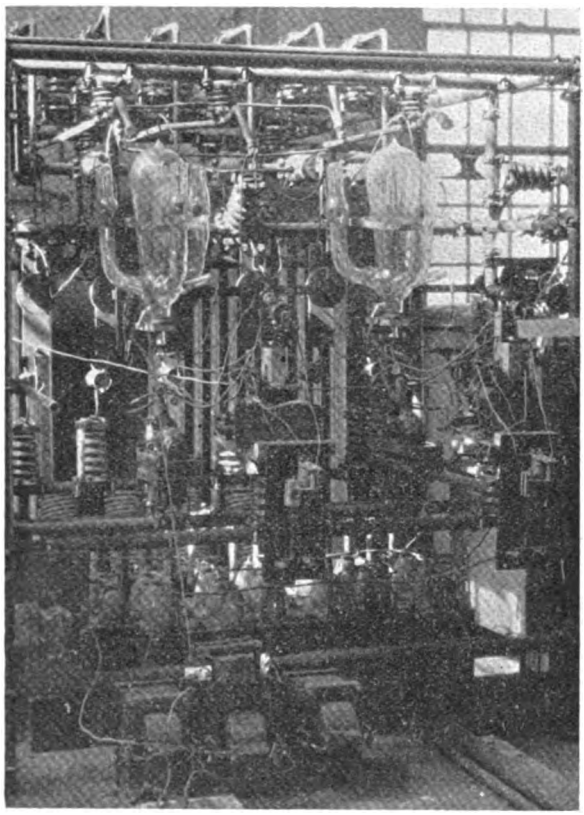

FIG. 2—AN EXPERIMENTAL INSTALLATION OF TWO THREE-PHASE RECTIFIERS

Connected in series to give 30 amperes at 10 000 to 15 000 volts. Condensers and choke coils are used to smooth out the ripple, which is very much less on a three-phase than on a single-phase rectifier.

ions. In a rectifier which is operating, the space above the cathode is filled with both positive and negative ions. Hence the breakdown voltage between a negative anode and the cathode should be lowered a great deal and backfiring should take place more readily. One way of nullifying the effect of the positive ions is to place sharp bends in the anode arm. The positive ion, since it is an ionized mercury atom, is heavy and is not easily deflected by an electrostatic field. Hence, in traveling a path with bends in it, it is prevented from reaching a high velocity and is condensed on the walls of the tube. Since the anode in this case is negative, the number of electrons in the vicinity of the cathode does not affect breakdown. However, should an anode which is negative, happen to be in such a state that it is emitting electrons, a breakdown will occur between the positive and negative anode. Such a case will be discussed later.

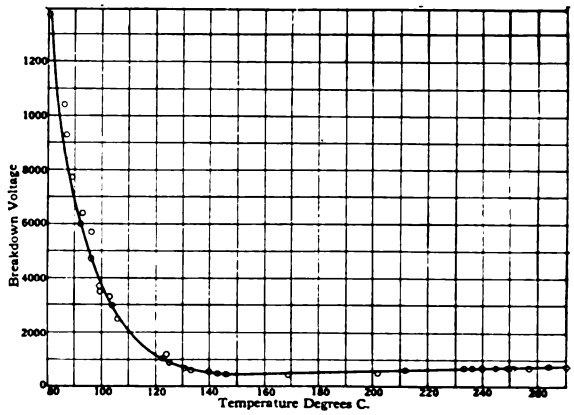


FIG. 3—THE BREAKDOWN VOLTAGE OF MERCURY VAPOR WITH TEMPERATURE

The anodes must also be protected from falling drops of mercury caused by the condensation of mercury vapor in the top of the anode arms. Should a drop of mercury strike the hot anode during the part of the cycle when it is negative, a cathode spot may be formed on the anode with consequent short-circuiting of the rectifier.

Considering the case of well-treated anodes themselves, the following causes of trouble may appear:—

1—High anode voltage drop and evaporation of the anode.
2—Sputtering of anode due to high voltage.

The anodes being in a closed vacuous space must lose all their heat by radiation. Hence it is essential

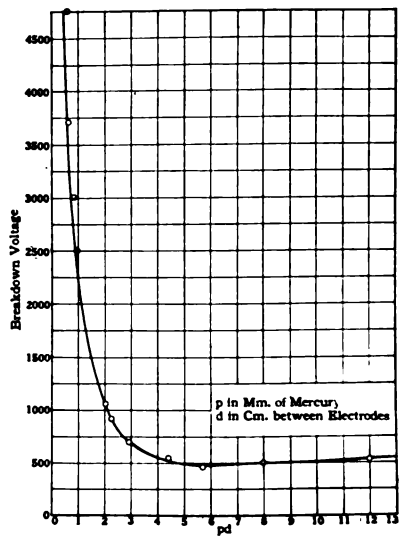


FIG. 4—THE BREAKDOWN VOLTAGE OF MERCURY VAPOR WITH PRESSURE AND ELECTRODE SPACING

to have the energy liberated at the anode as small as possible. It might be thought that all that is necessary is to increase the size of the electrode and so provide enough radiating area to maintain the temperature at a low value. However, if this is done, the amount of gas-containing material is increased and the

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removal of gases is made more difficult. The best way is to choose the shape and material of the anode so that the anode drop is low, and hence high temperatures do not result. There are two ways in which this can be accomplished.

Suppose that, of two disc-shaped anodes of the same size and material, one is placed in a large bulb and

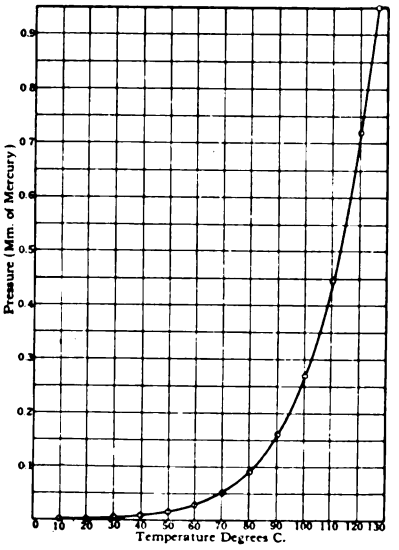


FIG. 5—THE VAPOR PRESSURE OF MERCURY WITH TEMPERATURE

the other in a tube which is slightly larger in diameter than the diameter of the anode. Suppose further that the two anodes operate at the same temperature. It will be found that the current to the anode in the large bulb is very much less than that to the anode in the small tube. An explanation of this phenomena has been given by Langmuir and Mott-Smith.

Assume a tube and an anode of unit cross-section which is carrying unit current. The electrons and positive ions in the discharge are moving about with a random motion upon which is superposed a drift motion due to the electric field existing between the anode and cathode. Let us suppose that the random current amounts to two amperes towards the anode and two amperes moving away from it. Hence the total current moving towards the anode is three amperes. Since the current in the external circuit is only one ampere, it is seen at once that the anode must acquire such a negative potential with respect to the gas space that two-thirds of the electrons which are moving towards it will be repelled, and therefore a negative anode drop is established. Now suppose that the area of the anode is reduced so that it is only one-third that of the tube. Then in this case the current spontaneous flowing towards the anode is just equal to the current flowing in the external circuit and the negative anode drop disappears. If the area of the anode is still further reduced, the random current to the anode is less than that flowing in the external circuit. Hence there must be a concentration of field in the vicinity of the anode which will cause the required number of electrons to be collected. Hence by correctly proportioning the size of the electrode and the space surrounding it, the anode drop and consequently the heating of the anode can be made small.

The second way of reducing the anode drop is by changing the shape of the anode. Assume two identical cylindrical anodes except that one shall have a small shallow hole drilled in the end facing the cathode. Suppose that these anodes are placed in identical tubes and run at the same current. The anode which has the hole in it will run at a lower temperature and the anode drop may be several volts less than the anode without the hole. The following is an explanation by Gunther-Schulze of this phenomena.

The anode is surrounded by a negative space charge which hinders electrons from reaching the anode. If there is some means of forming positive ions near the anode the effect of this negative space charge can be nullified, as one positive ion will neutralize the effect of several hundred electrons. We know that we can ionize a gas by resonance radiation. The mercury arc, of course, contains radiation which can ionize the mercury vapor near the anode, and can therefore produce the required number of positive ions provided the intensity of the radiation is sufficiently great. By having the anode face recessed, this radiation is prevented from escaping, as it is reflected from the metal faces of the recess, and hence it is possible to build up the intensity until the number of positive ions formed is sufficient to neutralize the space charge, thereby reducing the anode fall.

Langmuir, however, has experimental evidence which leads to another explanation. Suppose two positive plane electrodes are placed opposite one an-

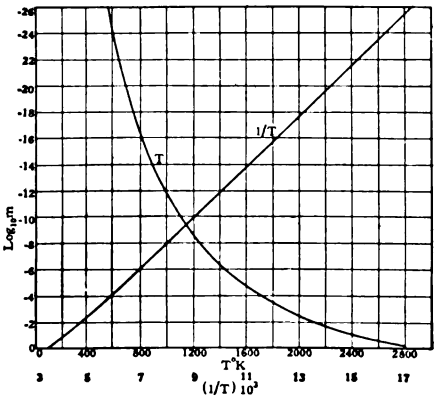


FIG. 6—RATE OF EVAPORATION, $m$, OF IRON
In grams per square centimeter per second.

other a distance apart equal to the mean free path of the positive ions. The two anodes will be surrounded by a negative ion or electron sheath. As the difference in potential between the anode and the surrounding space increases, ionization by collision takes place within the electron sheath. The positive ions so generated are ejected from the one sheath and enter the other, thereby causing a breakdown of the electron sheath and consequent lowering of the anode drop.

The effect of temperature on the evaporation of

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iron is shown in Fig. 6.* The evaporated iron deposits on the glass walls of the rectifier and eventually will cause a short-circuit between the anode and cathode. However, before this happens, the coating of iron on the walls near the anode will tend to act in the same way as a grid. This is likely to result in very high voltage surges which may injure the rectifier or its associated equipment. During the degassing treatment it is not possible to remove all the gas from the interior of the metal. Thus as the metal evaporates, small amounts of gas will be liberated which may ruin the vacuum in the container. Hence it is seen that the anodes should run at as low a temperature as possible to avoid evaporation.

The anode drop varies greatly with the mercury vapor pressure. From some data by Gunther-Schulze the drop over the anode was 7.08 volts at a pressure of 0.045 mm. (68 deg. C.), while it was 5.22 at 0.14 mm. (88 deg. C.). At the lower pressures the anode drop rises very rapidly with small decreases in pressure. In high-voltage rectifiers the pressure should be as low as possible, which produces high anode drops. Hence it is essential to design the anodes so as to reduce this drop as much as possible.

There is still another effect which causes a metallic deposit to form on the glass walls of the anode arms. This effect is called sputtering and may be classed as highly localized temperature evaporation of the surface considered. A surface can sputter when it is made either the anode or the cathode of a glow discharge. The anode sputtering, however is small, the cathode sputtering being much larger, since it is due to bombardment of the surface by positive ions.

The amount of material sputtered from the electrodes increases with:—

1—Pressure of gas
2—Current to electrode
3—Decreasing distance between electrodes
4—Cathode voltage drop.

and also depends upon the kind of metal used as electrode, its shape, and the nature of the gas used.

The results obtained to date by various investigators are rather contradictory. Sputtering may be affected greatly by the gas through chemical action, and by the coats of oxide or gas on the surface. It appears that graphite is the best substance to use in a mercury rectifier from this point of view.

*Taken from the data of Jones, Langmuir and Mackay, *Phys. Rev.*, Vol. 30, p. 201, 1927.

# Fluid Governors for Prime Movers

## V—Governing Impellers

HENRY F. SCHMIDT

PROBABLY the first question which occurs to the reader in studying the impeller of an oil governor is the amount of power required. In the smaller machines where no ejector is employed, and the impeller only furnishes pressure to a direct-acting operating piston, the power consumption is less than where an ejector and relay mechanism are employed.

In general, the power required to drive a disc or impeller in a smooth housing filled with liquid is expressed by the formula,—

$$Hp = KD^2\left(\frac{V}{100}\right)^3$$

in which $V$ is the tip velocity in feet per second, and $D$ is the tip diameter in inches. This formula would also hold where the discharge varies a relatively small amount compared with the normal capacity of the impeller, and where the impeller is made very large for the maximum volume which it is required to deliver.

Also, the power required by an oil impeller depends upon the viscosity and the temperature of the lubricating oil. However, at the ordinary operating temperatures encountered in turbine practice, the difference in viscosity of the commonly used lubricating oils is not great. For the average light turbine oil generally employed, the value of $K$ in the horse-power formula may be taken as 0.11, and for governing systems in which ejectors and relay valves are used, $K$ may be equal to 0.125. The reason for the small difference between these two constants is that almost the entire power put into the impeller is used in friction, and very little in the actual work done in pumping, so that the total is not seriously influenced by the quantity of oil delivered. Also, these constants apply to large slow-speed impellers as well as the smaller high-speed impellers, but generally speaking, the actual pumping work done is about proportional to the size of the impeller, so that the value of the constant is not influenced much by the size.

The power varies approximately as the fifth power of the diameter at constant speed, and, as the pressure varies only as the square of the diameter, it is evident that it is undesirable to use too high a governing pressure in the smaller turbines, since this increases the power lost in the impeller. In the larger turbines, the governing pressure is generally 50 to 60 pounds, but this is reduced to as low as nine or ten pounds in the smaller machines.

Where a governor is intended to be adjusted to operate at widely different speeds, however, it is necessary to design the impeller for a higher pressure at the higher speeds than would normally be employed, since the pressure varies as the square of the speed, and if the turbine must govern at one-tenth speed, the governing pressure available is only 1/100 of the pres-

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sure at the maximum speed. However, the governing piston is so sensitive that no difficulty has been encountered in a number of machines designed for a maximum pressure of 65 pounds and a speed ratio of over 8 to 1. In other words, the governing pressure at the lower speed is slightly under one pound. Of course, it is obvious that unless multiple springs or a spring with a variable scale is employed, under these circumstances the percentage speed variation is very large at the lower speeds, even if it is only one or two percent at the higher speeds.

An impeller combined with a double Kingsbury thrust bearing is shown in Fig. 40. This thrust bearing is designed to take the principal thrust towards the exahust end of the turbine. Therefore the Kingsbury shoes *A* have considerably greater area than the shoes *B*, which are only provided to prevent the spindle from moving towards the inlet end when steam is shut off. The thrust collar *C* has an extension *D*, which has an annular recess *E* for the entrance of the oil. Radial passages from the inlet *B* to the periphery are provided by means of a number of drilled holes. These

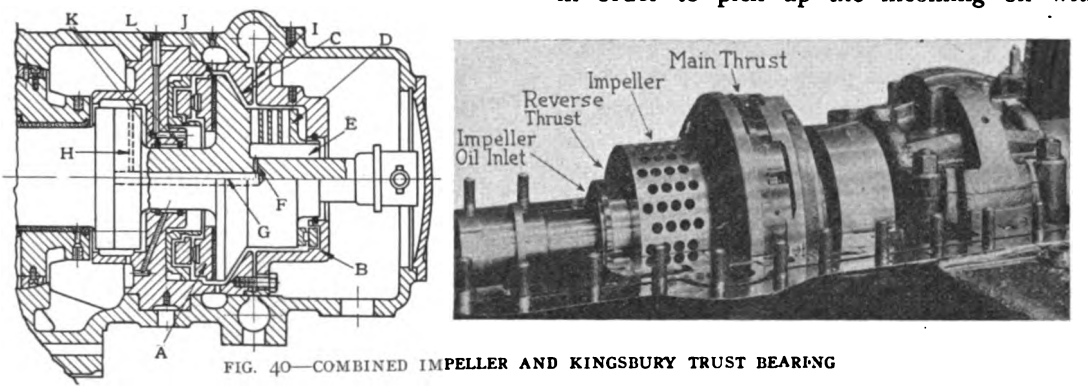


FIG. 40—COMBINED IMPELLER AND KINGSBURY TRUST BEARING

holes are sufficient in size and number so that the velocity of the oil through them is very low, permitting the separation of air from the oil. The air, being lighter than the oil, is forced to the center and escapes through radial holes *F*, and the axial hole *G*, which in turn communicates with the bearing housing through the radial holes *H*. The oil discharged by the impeller passes through a narrow radial circumferential slot *I* into the collecting chamber from which it is delivered to the governing mechanism. As the discharge pressure from the impeller is communicated to the passage *J*, and into the Kingsbury thrust bearing, packing rings *K* are provided to prevent the escape of oil into the bearing housing. In this particular design, the passage *L* from the thrust bearing chamber is provided through which the high-pressure oil for operating the ejector is withdrawn, thus insuring a definite supply of oil to the thrust bearing.

In connection with Fig. 40, the writer believes that a considerable advantage is gained in subjecting the thrust bearing to a pressure of 50 or 60 pounds per square inch where the surface speed is high, as there seems to be good evidence that a time-element factor, which is not generally taken into consideration, enters into the lubrication problem. This may be due to the fact that as the thrust collar comes out from under one shoe, only a very short time interval elapses in which the collar can be rewet and sufficient oil adhere to it to establish an adequate oil film under the next shoe. If this should ultimately be shown to be a fact, subjecting the thrust bearing chamber to pressure would be advantageous, as it is evident that the higher the pressure, the shorter the interval required to reform the oil film.

The most obvious advantage of the arrangement shown in Fig. 40 is that the impeller absorbs only that additional power required to do the actual pumping of the oil handled, since the thrust collar is required in any event and its friction loss is approximately the same whether it is used simply as a thrust collar or as a thrust collar and an impeller combined.

A type of impeller is shown in Fig. 41, which has been extensively employed. This is of the plain paddle-wheel type, with straight radial vanes which, however, are provided with forwardly tipped curved inlet edges in order to pick up the incoming oil with as little shock as possible. The oil enters the impeller through stationary guide vanes *A*, which simply serve to keep the oil from rotating before entering the impeller. The guide vanes project into the undercut portion of the impeller and the pumping function of the impeller is performed solely by the narrow portion *B*. The remaining portion of the impeller width is solely to remove the entrained air from the oil. The difference in density between the oil and air is so great that under the action of centrifugal force, the air moves to the point of minimum pressure at the hub of the impeller and escapes through the annular passage *C* around the shaft and the drilled hole *D*, which communicates with the oil reservoir. A sealing ring *E* is provided around the shaft to prevent an excess of oil entering the bearing housing.

The oil discharged by the impeller enters the collecting chamber *F*, through the annular passage *G*, which is sufficiently narrow and exposes sufficient friction surface to prevent any inertia effect of the mass of oil rotating within it. The sealing ring *H* is provided simply so that all the oil entering the impeller must pass through the guide vanes and thus have an

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axial motion imparted to it, since the oil in the inlet chamber rotates due to the presence of the automatic stop on the end of the shaft.

When the speed of rotation is low, a very large diameter impeller is needed in order to get the pressure required for governing without going to excessive governing piston diameters. This, however, is undesirable,

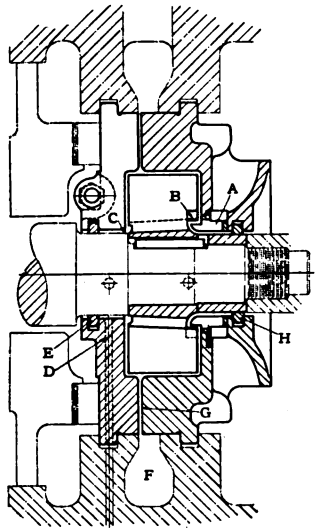


FIG. 41—PADDLE WHEEL TYPE OIL IMPELLER

as was seen from the formula given for the power consumption of the impeller, since the power increases as the fifth power of the diameter and the square of the revolutions per minute. Obviously, the power consumption at low shaft speeds can be reduced by using multiple runners, as is done in high lift and slow-speed centrifugal pumps.

A two-stage governor impeller is shown in Fig. 42. It will be noted that the two impellers are not alike, the first impeller being very wide compared with the second. The first impeller serves as the air separator, the air disengaged by centrifugal force escaping through the radial holes *A*, the axial hole *B*, and radial holes *C*, which discharge air into the bearing housing. The

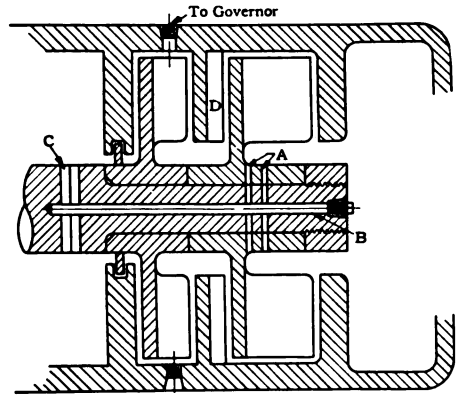


FIG. 42—A TWO-STAGE IMPELLER WITH AIR SEPARATOR

radial holes *C* are always larger than the holes *A*, in order that they will not act as centrifugal pumps, the area of the holes *C* being made sufficient that the column of liquid will break, preventing any pumping action. These passages are, therefore, left free for the escape of air.

Guide or stationary vanes *D* are provided between the first and second impellers to prevent rotation of the oil in the inward flow to the second impeller. The second impeller may be designed as an ordinary pump runner, as the air separation has been performed by the first one of the series. Where more than two impellers are employed, all the succeeding impellers may be designed similar to the second one.

In Fig. 42 no guide vanes are shown in the inlet to prevent rotation of the oil before entering the impeller. It has been found that the use of the inlet guides is optional, and that equally good results in air separation are obtained by using an inlet chamber of the volute type, imparting a definite rotation to the oil in the direction of motion before it enters the impeller. The omission of the inlet guides is of course, desirable where the design conditions permit, as it avoids having the projecting fingers inside the runner. It has also been found, however, that either the oil must have a definite rotation imparted to it in the direction of motion by a volute shaped inlet, or else all rotation must be taken out of the oil before it enters the runner. Apparently, in the intermediate condition eddies are set up in the inlet chamber, resulting in an uneven flow into the impeller which causes fluctuations

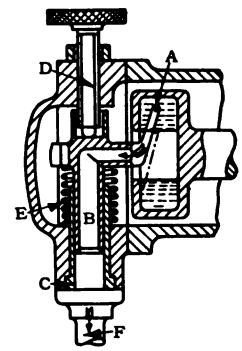


FIG. 43—A BOWL-TYPE IMPELLER

in the discharge pressure and also interferes with the air separating ability of the impeller.

A clever method of overcoming the great change in head due to change of operating speed is shown in the design of Fig. 43. This impeller is of the scoop type, in which a Pitot tube is led into a rotating annulus of oil. The novel feature consists in having the Pitot tube arm movable radially. At high speeds, the point of the tube is moved towards the center, and at low speeds towards the maximum diameter of the annulus, thus permitting a change of governing speed without changing the tension of the governing spring. This scheme also has the advantage that, within the range of pressures obtainable between the inner and outer radii, the speed variation of the turbine will remain constant, since the governing pressure, neglecting speed variation, will remain constant. This device, however, is open to the objections previously enumerated, that its capacity is so limited that it would be suitable only for very small machines, and not for turbines having oil relays or ejectors. Further, since the oil is removed from the annulus due to leakage in the operation of

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the governing cylinder, a pump or other means must be employed for keeping the annulus replenished with oil. Where a separate supply line is employed for subjecting the governing piston to oil pressure and a separate line for supplying the relay valve, as in Fig. 39, the objections of the Pitot tube design can be overcome by employing the Pitot tube for supplying the

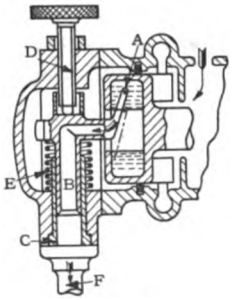


FIG. 44—A BOWL-TYPE IMPELLER WITH CENTRIFUGAL PUMP

governing pressure and an impeller mounted on the back of the Pitot tube bowl for supplying the oil for operating the ejector, relay mechanism and bearings and replenishing the oil in the Pitot tube bowl. This is shown in Fig. 44.

In the impeller arrangements previously discussed, all the shafts were presumably horizontal and ended in the oil inlet chamber. An unusual case is shown in Fig. 45, in which the shaft is vertical and extends

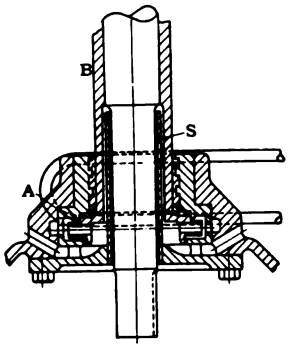


FIG. 45—OIL IMPELLER FOR A VERTICAL TURBINE

through the bottom of the oil reservoir. In this case, the oil impeller *A* is integral with the sleeve, *B* shrunk on the shaft, the oil passages for the impeller consisting of radial holes into an undercut in the impeller. The sleeve *B* also acts as the lower bearing journal. The normal oil level in the reservoir is as shown, and oil is prevented from escaping along the shaft without the use of a stuffing box by means of the sleeve *S*, which forms a part of the lower impeller chamber cover, and extends up above the oil level in the annular space between the sleeve *B* and the shaft. In this case the impeller is relatively narrow, as it is used only for a direct-acting governor piston, and for supplying a very small nozzle for circulating the oil over the cooler in the oil reservoir. Air separation is, therefore, obtained without great axial width.

A wide impeller, as indicated by Reichenbach, Fig. 5, is also shown by Smoot, Fig. 46. In addition to providing a wide impeller, Smoot has also shown an inlet tube extending into the inside of the impeller, and a close fitting ring around the periphery; the tube and ring having radial holes, the object of which is to prevent the fluid from rotating before it enters and after it leaves the impeller. Thus it is sought to have only a fixed radial depth of fluid rotating and subjected

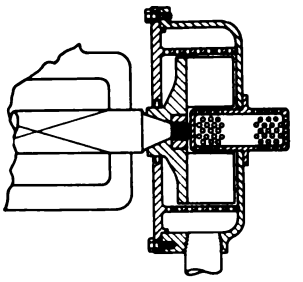

FIG. 46—SMOOT OIL IMPELLER

tc centrifugal force, in order to avoid the pressure pulsations commonly encountered in centrifugal pumps, and obtain a pressure which is exactly proportional to the square of the speed.

Another arrangement of securing a constant oil pressure to the relay for governing in place of the arrangement shown in Fig. 44 may be obtained by the use of two impellers.

One of the impellers is used to supply the governing oil for moving the relay and the oil for operating the ejector. The second impeller furnishes only the operating oil for moving the operating piston and furnishes the supply to the bearing. Thus by eliminating the variable flow from the impeller supplying the governing oil and the oil to the ejector, the steadiness of the oil delivered by the ejector is improved as is also the governing oil pressure. This is the arrangement employed on a 60 000 kw turbine for Milwaukee.

*(To be continued)*

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# Methods of Testing Electrical Apparatus

## XXV—Transformers

THE first precaution before starting a test on a transformer is to see that it is completely assembled, with all outgoing leads and terminal bushings in place. Since the oil in oil-insulated transformers is used for insulation as well as for cooling, it follows that all oil-immersed transformers should have clean dry oil at the proper level before any tests are made. In the factory, for convenience, tests, with the exception of temperature tests, are made on single-phase distribution transformers rated at 3500 volts or less without the use of oil. However, for power transformers and for distribution transformers whose rated voltage is above 3500 volts, the rated voltage is the limiting value which may be used in making any tests with the transformer out of oil. Transformers above 33 000 volts should always be tested under oil.

### CLASSIFICATION OF TESTS

*Complete Tests* consist of commercial tests and of normal and overload temperature tests.

*Commercial Tests* for power transformers consist of determining the resistance and ratio, checking the taps, polarity, core loss and exciting current, measuring the copper loss by a wattmeter, impedance and insulation tests. These are applied to all transformers, except that copper loss and impedance are omitted on duplicate units of medium and small capacities. For distribution transformers, the tests should be the same as for power transformers, except for the copper loss. impedance and resistance, which can be omitted on duplicate units.

### ORDER OF TESTS

The usual order of conducting the tests is as follows:—

1—Measurement of resistance.
2—Ratio and polarity test.
3—Parallel test.
4—Measurement of core loss and exciting current.
5—Measurement of copper loss and impedance.
6—Temperature tests.
7—Insulation resistance test.
8—Dielectric tests.

This order may be modified in some cases; however, only the resistance test should be made before making the ratio and polarity test. Tests 6, 7 and 8 should be made in the order given.

The tests to be applied to the different types of constant potential transformers are very much alike; therefore, a complete discussion for only one type will be given, namely, the oil-insulated, self-cooled. For the other types, a partial discussion will be given and reference made to the OISC.

### MEASUREMENTS OF RESISTANCE

Since the methods commonly employed and the general precautions to be observed in making resistance measurements have been previously described*, only a brief discussion of this subject will be given here.

The usual practice is to measure the resistance of the total high-voltage and total low-voltage windings. However, if efficiency guarantees are given, or a temperature test specified for a voltage ratio that would include less than the full windings, resistance measurements must be made in accordance with these requirements.

Every possible precaution should be taken to obtain the true temperature of the windings when measuring the cold resistance. The temperature of the surrounding air must not be regarded as the temperature of the windings. If the measurements are made with the transformer out of oil, thermometers should be well inserted between the coils in order to be as close as possible to actual contact with the copper of the winding. If the transformer is immersed in oil prior to making the measurements, the temperature of the oil may be taken as that of the windings, provided a period of six or eight hours has elapsed between the time of putting in the oil and that of making the test, and provided the ambient temperature has not greatly changed in that time.

All electrical contacts, link connectors, and locking nuts included in the circuit being measured, must not only be clean and tight, but must make good contact as well. Select such positions on the transformer leads or terminals for connecting the resistance measuring bridge leads as may be readily duplicated when taking the hot resistance measurements.

When using the Kelvin Bridge, the order of procedure is as follows: Connect the bridge leads to the leads of the winding to be measured. Insert the connecting plugs of the standard resistance and ratio coils of the bridge to approximately the resistance value to be measured. Close the switches of the battery and the potential lead circuits, battery switch first, and then gradually increase the current, by rheostatic control, until it reaches a value which has been predetermined by the current rating of the bridge or the winding being measured. Next close the galvanometer circuit and make the final adjustment by moving the slide contact until the galvanometer deflection indicates a balance. The current must attain its constant value before taking the final reading, otherwise the indicated resistance will be erroneous. If the winding being measured has an appreciable time constant thereby tending to retard the increase of the current, the rheostat should be cut out of the circuit rapidly and then gradually cut in again until the desired cur-

*In the JOURNAL for April, 1925 page 191.

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rent value has been reached. When switching off the current, the bridge equipment should be protected from an induced voltage discharge, by reversing the sequence of operations used when applying the current.

The wiring connections between the bridge and galvanometer are so made, with regard to polarity, that when the slide contact is moved in either direction, the galvanometer will deflect in the same relative direction. This relation is not highly essential, but it obviates confusion in the mind of the operator and tends toward hastening the operation of measuring, which is very desirable, especially when measuring hot resistances.

When using the Wheatstone Bridge, the sequence of operation is carried on in a manner similar to that described for the Kelvin Bridge, except that no attempt is made to vary the current when applying it to the windings.

When it becomes necessary to use the drop of potential method, the following precautions should be observed. In some cases, the pointer of the voltmeter will fluctuate rapidly, thereby making it impossible to get satisfactory readings. This is due to small increments of change in the magnetic flux of the core which, in turn, produces fluctuating e.m.f.'s in the winding. In such cases, the opposite winding from that being measured should be short-circuited. This action will be effective in damping out the voltage fluctuations. Unless the current in the winding being measured has become practically constant before the short-circuit is applied, the indicated resistance values may be erroneous. Disconnect the voltmeter from the circuit before switching the current on or off, in order to protect it from an induced voltage discharge.

All resistances should be recorded as measured, but for comparative purposes, they should also be corrected to an equivalent value corresponding to a temperature of 75 deg. C. A resistance value may readily be changed from that at one temperature to that at another by use of the formula:*—

$$\frac{Rt}{Rt'} = \frac{234.5 + t}{234.5 + t'}$$

where $Rt$ equals the cold or initial resistance measured at $t$ degrees and $Rt'$ equals the resistance corresponding to a temperature of $t'$ degrees.

### RATIO

The ratio of a transformer, unless otherwise specified, is equal to the ratio of the number of turns in the high-voltage winding to the number of turns in the low-voltage winding. It is important that the ratio test should be carefully conducted. An error in the number of turns of either winding, if not discovered and corrected, will not only affect the voltage ratio, but may also cause undue heating if the transformer should be connected in parallel or in delta with other units having the correct ratio.

*See the JOURNAL for Jan. 1926, page 43.

The test is usually made by applying voltage equivalent to one volt per turn, at normal frequency or lower, to the total high-voltage winding. By this method, the turn values may then be read directly in volts. If one volt per turn will not give a readable deflection on the most accurate part of the voltmeter scale, the voltage may be increased to two or four volts per turn, provided the total voltage does not exceed the normal rated voltage of the windings, nor cause excessive induction in the iron. If, for any reason, it becomes necessary to make the test on a core type transformer out of its tank, the transformer should not be placed near a circuit carrying a high current of the same frequency as that being used in the test. This is a precautionary measure to eliminate the effect of stray field from the circuit, which might

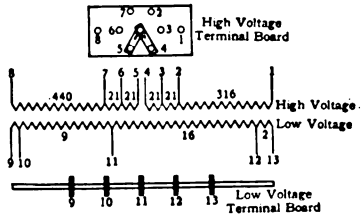


FIG. 109—DEVELOPMENT OF WINDINGS AND TERMINAL BOARDS OF 13 200 TO 440 VOLT O.I.S.C. TRANSFORMERS

magnetize a portion of the core and thereby cause erroneous results in the voltage ratio even though the turn ratio is correct.

### PROCEDURE FOR RATIO TEST

Consider first a single-phase, 60 cycle transformer having a nominal voltage rating of 13 200 and 440 volts, the high-voltage winding having 840 turns and the low-voltage winding 28 turns. Each winding is also provided with several taps. A development of the winding, giving the number of turns and the location of taps of the respective windings, together with the terminal boards, showing the numbering and position of the terminals, is shown in Fig. 109.

The first operation is to remove all link connectors used for connecting the sections or groups of the high-voltage winding. Then, with a suitable lighting out circuit, approximately 100 volts with a lamp in series, check the terminals representing the ends and taps of the windings for position. It is good practice to have the opposite winding short-circuited when making this test. Repeat the operation for the low-voltage winding when it is divided into two or more parts. Having completed this operation, replace the link connectors, making the connections that will put all parts of the respective high-voltage and low-voltage windings in series. Next, apply a low voltage to the total high-voltage winding, terminals 1 and 8, in order to check the numbering and position of the terminals. Usually 100 volts is a sufficiently high value. Read the voltage values of 1 to 8, 1 to 7, 1 to 6, 1 to 4, 1 to 3 and 1 to 2. The above readings should give successive lower voltage values, as the number of turns between measuring points is decreased. These

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readings will indicate whether the terminals are properly arranged and numbered on the terminal board and will also serve to detect any transposition of taps.

To determine the overall and tap ratios of this transformer, two volts per turn should be used. This will be a convenient value and will permit the use of one voltmeter throughout the test provided a suitable transformer is used on the high-voltage side. Apply two volts per turn, which is 1680 volts, to the total high-voltage winding 1 to 8, Fig. 109, and read the voltages from:—

2 to 3 = 42 volts = 21 turns
5 to 6 = 42 volts = 21 turns
3 to 4 = 42 volts = 21 turns
6 to 7 = 42 volts = 21 turns
2 to 4 = 84 volts = 42 turns (check)
5 to 7 = 84 volts = 42 turns (check)

Keeping the voltage impressed on the high-voltage winding at two volts per turn, read the voltage of the low voltage winding, as follows:

9 to 13 = 56 volts = 28 turns
10 to 13 = 54 volts = 27 turns
11 to 13 = 36 volts = 18 turns
9 to 12 = 52 volts = 26 turns

A sufficient number of observations should be made in each case to establish, beyond doubt, that the readings are correct.

For another example, take a single-phase core-type transformer having a nominal voltage rating of 33 000 and 2300 volts, the high-voltage winding having 9758 turns and the low-voltage winding 680 turns. The development of windings, position of taps, and the number of turns in the respective windings are shown in Fig. 110. The taps should be stepped out for position and numbering in a manner similar to that described for the previous test. It may be more satisfactory to use two or three hundred volts instead of one hundred.

The ordinary method of checking the tap values may prove unsatisfactory in this case, or in a similar case when the transformer is of the core-type. Owing

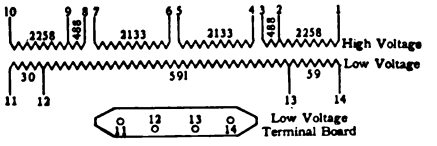


FIG. 110—DEVELOPMENT OF WINDINGS AND TERMINAL BOARD OF 33 000 TO 2300 VOLT O.I.S.C. TRANSFORMERS

to the physical arrangement of the coils, the reactance is comparatively high when using the total high-voltage windings as a primary and a comparatively small portion of the same winding as a secondary. Consequently, if a small percentage of the normal rated voltage is applied to the total high voltage winding and a voltmeter is connected to two intermediate taps, the current taken by the voltmeter may cause a reactance voltage drop sufficient to indicate an erroneous turn ratio, even though the actual turn ratio is correct. The error will vary in magnitude, depending upon the kv-a rating of the transformer, the rated voltage and the percentage of normal rated voltage used in making the test.

To check the tap ratio of a transformer of this description, the same method which is applied in checking the ratio of the total high-voltage turns to the total low-voltage turns should be used throughout. This is done by cutting out sections of the high-voltage winding, one after another, taking each tap consecutively and applying voltage proportionately less in each case to the remainder of the high-voltage winding. The volts per turn will thus be kept constant; hence,

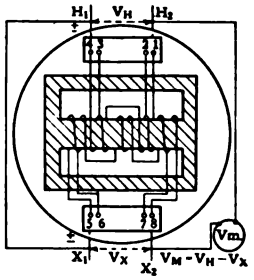


FIG. 111—TRANSFORMER LEAD MARKINGS FOR SUBTRACTIVE POLARITY

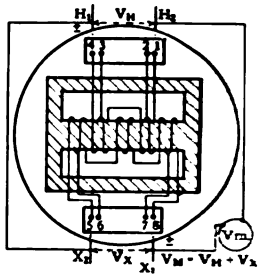


FIG. 112—TRANSFORMER LEAD MARKINGS FOR ADDITIVE POLARITY

the voltage of the low-voltage winding will be kept constant in value throughout the test.

In this case, one-half volt per turn is a convenient value to use. Since there are 9758 turns in the total high-voltage winding, 4879 volts should be applied to the high-voltage winding, terminals 1 and 10, which should develop 340 volts in the total low voltage winding. The applied voltage may be supplied by a suitable step-up transformer. The low voltage can be read conveniently by means of a voltmeter having a 600 volt range. After having checked the ratio of the total winding, the taps should be checked in the following manner:—Disconnect terminals 3 and 4, and connect terminals 2 and 4 instead, then, apply 4635 volts to terminals 1 and 10 and again read 340 volts on terminals 11 and 14. Tap 9 should be checked by applying 680 volts (one volt per turn) to terminals 11 and 14 and reading the voltages from 11 to 12 = 30 volts or 30 turns; 13 to 14 = 59 volts or 59 turns.

In all cases, a sufficient number of readings must be taken to establish beyond doubt that the turn ratio is correct. This condition is considered as being met when the ratio involved is correct within two-tenths of one percent. If an error is discovered in the turn ratio, all parts of the winding must be carefully checked and the part which is wrong should be definitely located and a complete report made so that the error may be rectified with the least possible expenditure of time and labor.

## POLARITY

The polarity of a transformer is denoted by the relative locations and markings of the high-voltage and low-voltage outlet leads, with respect to the sign of their potential difference at any instant.

The Standards of the *A.I.E.E.* (No. 13, August, 1925), specify that "the leads brought out of the case shall be distinguished from one another by marking each lead with a capital letter followed by a number.

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The letters to be used are:—$H$ for high-voltage leads; $X$ for low-voltage leads and $Y$ for tertiary winding leads. The numbers to be used are 1, 2, 3, etc." "All numbers shall be so applied that the potential difference from any lead having a lower number toward any lead having a higher number shall have the same sign at any instant."

"The numbering of the high-voltage and low-voltage leads shall be so applied that when $H_1$ and $X_1$ are connected together and voltage applied to the transformer, the voltage between the highest numbered $H$ lead and the highest numbered $X$ lead shall be less

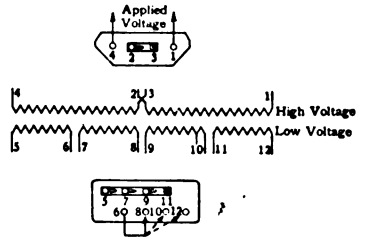


FIG. 113—CONNECTIONS USED IN PARALLEL TEST ON LOW VOLTAGE WINDING OF A POWER TRANSFORMER

than the voltage of the full high-voltage winding". This denotes that the potential difference from $H_1$ towards $H_2$ has the same sign at any instant as the potential difference from $X_1$ toward $X_2$.

"When the leads are marked in accordance with the above rules, the polarity of a transformer is: Subtractive when $H_1$ and $X_1$ are adjacent, and additive when $X_1$ is diagonally located with respect to $H_1$", as shown in Figs. 111 and 112 respectively. "Transformers having their leads marked in accordance with these rules may be operated in parallel by connecting similarly marked leads together, provided their ratio, voltages, resistances and reactances are such as to permit parallel operation".

The Westinghouse Company's practice is to build all single-phase power transformers to have subtractive polarity, except in some instances where the customer requests it to be the reverse. The $H_1$ lead is usually brought out of the case or tank on the right-hand side, facing the high-voltage side of the case. Distribution transformers, however, may have either subtractive or additive polarity, depending upon their normal high-voltage rating. When the normal high-voltage rating is above 7500 volts, they are designed to have subtractive polarity. When the rated high voltage does not exceed 7500 volts, they are designed to have additive polarity.

The relative order of numbering the winding terminals inside of the case is from the right hand side toward the left on the high-voltage winding and from the left hand side toward the right on the low-voltage winding, facing the low-voltage side of the case. Do not confuse the numbering of the winding terminals with the numbering of the leads brought out of the case. The test made to determine the correctness of the markings and relative locations of the high-voltage and low-voltage leads is termed the polarity test. A convenient time to make the test is immediately after making the test for the position of taps and arrangement of the terminals.

### STANDARD POLARITY TEST PROCEDURE

The standard method of conducting the test is as follows:—Connect the adjacent left-hand high-voltage and low-voltage leads together, facing the low-voltage side of the transformer. Apply a convenient value of voltage to the total high-voltage winding and take readings of the applied voltage and the voltage between the right-hand adjacent high-voltage and low-voltage leads. As power transformers are being considered at present, the latter voltage reading should indicate the arithmetical difference between the voltage of the two windings. If the latter reading indicates the sum of the voltages, the cause should be investigated and corrected.

### PARALLEL WINDING TEST

Any transformer in which the windings are divided into sections, and the sections so arranged that they may be connected in parallel, or in series parallel for normal operation, must be given a parallel test. The test is made to determine whether there is any circulating current in the windings when the separate sections are connected to operate in parallel. Contributory causes for circulating current are: unequal numbers of turns in the respective sections to be connected in parallel; and small differences between the induced voltages of the respective sections, due to magnetic leakage.

### PROCEDURE FOR PARALLEL TEST

The procedure for parallel test may be better understood from the following example:—Consider a

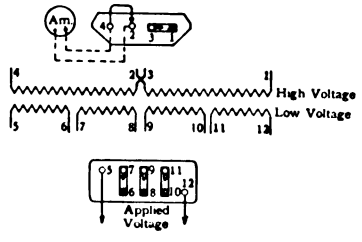


FIG. 114—CONNECTIONS USED IN PARALLEL TEST ON HIGH VOLTAGE

transformer having its windings divided into sections similar to that shown in Figs. 113 and 114. Connect one lead from each section of the low-voltage winding to a bus bar in such a manner that the polarity of each lead is the same. In the example, the proper method would be to connect terminals 5, 7, 9 and 11 on the terminal board by connectors provided for that purpose. Then, connect one end of a fine wire to terminal 6 and the other end of the wire to the end of a clean, dry stick (one that may be handled with perfect safety) in such a manner as to leave a short piece of wire free. Apply about ten percent of normal voltage to high-voltage terminals of the transformer. The end of the wire should then be touched in succession to terminals 8, 10 and 12. If no spark is observed

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in any of the parallels, normal voltage should then be applied and the operation repeated.

The sections of the high-voltage winding should be tested in the same manner as that described for the low-voltage winding. Terminals 1 and 3 should be connected together on the terminal board. A low voltage should then be applied to the low-voltage windings, connected in series, and terminals 2 and 4 touched together by means of the stick and wire as described for the low-voltage winding. If the spark appears in the parallel, connect an ammeter, having a low impedance, in the circuit at the place where the spark is observed. Then with normal voltage applied to the transformer, read and record the value of the circulating current. In some cases, it may be preferable to read the voltage which tends to circulate the current, rather than the current itself.

When circulating current is in evidence, the cause for its presence should be determined. A very careful check of the ratio test will usually reveal whether it is due to an error in the number of turns or to magnetic leakage. If an error is found in the number of turns, the transformer must be corrected for that fault. If the circulating current is due to magnetic leakage, it should not exceed five percent of the rated current of the winding. In any case where doubt exists regarding the correctness of the turns of a transformer, a parallel test should be made in connection with another unit of the same type of which the ratio is known to be correct.

*Caution*—Extreme care should be taken, when making the parallel test, not to touch any two terminals of opposite polarity, since the resulting short circuit might prove disastrous to both tester and apparatus.

*(To be Continued)*

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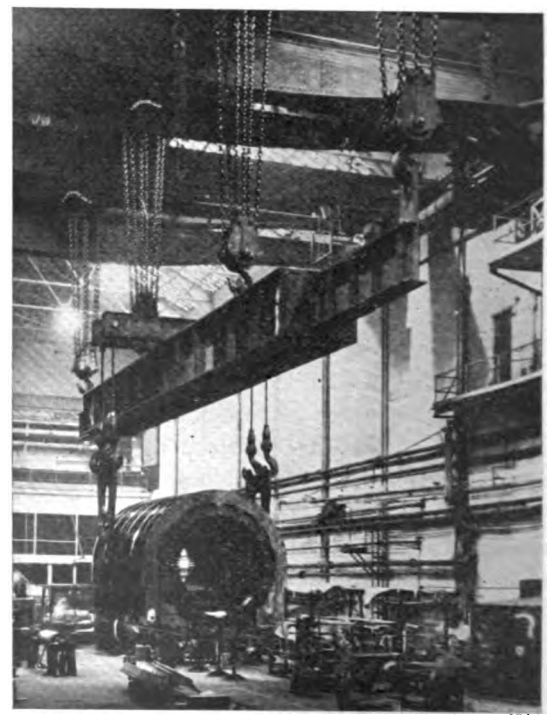
## A Four Crane Team

THE electrical industry keeps on calling for even larger and larger machines. Furthermore, it insists that the machines be shipped complete and not in sections as the assembling and testing can be done so much more easily and quicker in the manufacturer's plant. As a result the handling facilities and ingenuity of plant engineers, railroad companies and installation men have been severely taxed. In some cases, railroad companies found their standard cars inadequate and had to build special ones in order to haul the heavy machines. In the shop the scheme shown in the illustration was devised to avoid installing larger cranes—which would have required rebuilding the crane runways to carry the concentrated loads. With this lifting beam four cranes can be operated in parallel as shown. In this particular case, the load consisted of a one hundred ton stator for a 69 000 kv-a turbo-generator.

In order to divide the load evenly between the four cranes, the beam was built on the principle of the double tree. The two smaller beams to which the cranes are attached are fastened to the ends of the main beam with two large steel pins, forming two bearings. The two short beams shown laid cross-wise on the main beam, and carrying the four lifting hooks, are only clamped to the main beam so they can be moved along it. Thus the cross beams can be adjusted to suit the load.



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This beam was fabricated entirely by arc welding as tests have proved that an arc welded structure is considerably stronger than a riveted one of the same weight. In this case, the arc welded beam weighs 41 tons. If rivets had been used it would have weighed 55 tons, thus 14 tons of metal were saved and, what is more important, 14 tons added to the lifting capacity of the four crane team.

Lifts are made with this method with surprising speed and smoothness, no difficulty being experienced in getting the four cranes to work together smoothly. On the first lift practically no instructions were given the crane operators but the life was made without difficulty.

## Fusing Instrument Transformers

IT IS practically impossible to protect an instrument voltage transformer with fuses. A fuse wire small enough and long enough to open the transformer circuit with certainty during an overload would be mechanically too frail. Sometimes voltage transformers have been connected directly to the lines without fuses, but this is dangerous, because a short-circuit within the transformer might cause a high-voltage lead to burn off and fall in such a way as to short-circuit the system.

To prevent this, it is better to use resistors and fuses in the high-voltage leads of voltage transformers. The resistors limit the short-circuit current to 20 to 40 amperes which can easily be opened by comparatively short and rugged fuses. In normal operation, the resistors carry only the small primary current of the voltage transformer, and the drop in voltage which they cause is inappreciable.

## Methods of Applying Relays to Circuit-Breakers

SMALL alternating-current circuit-breakers often have automatic characteristics built into them, in which case relays are not required. These self-contained automatic characteristics are simple and usually consist of plain over-current trip coils arranged so that they can be adjusted to operate on any desired current value, a common range being 4 to 8 or 12 amperes. Sometimes, these trip coils are equipped with simple time-limit devices such as dashpots, which are not accurate, but are reliable and, because of their simplicity, are in common use. Circuit breakers so equipped are used without relays on small feeders where there is a little need for the more highly developed, discriminating action of the relay.

Sometimes circuit breakers are equipped with low-voltage release coils, but from the consideration of continuity of service this is not desirable because circuit breakers so equipped will be tripped open whenever there is line trouble in the vicinity, even if the disabled line is automatically cleared from the rest of the system.

### DIRECT-CURRENT SHUNT TRIPPING

Where automatic circuit-breakers in themselves are not suitable, it is necessary to use relays. The simplest method of doing this is to place direct-current coils on the circuit breakers and connect the protective relays so that their contacts will close the tripping circuit whenever it is desired to open the circuit breakers automatically. This is known as shunt tripping. Most large circuit breakers are now electrically operated, and the trip coil to which the relays are connected is the same trip coil as that used during non-automatic operation of the breakers. Sometimes, however, the circuit breaker is closed by hand, and is supplied with a trip coil for automatic opening.

The question arises as to where to obtain power for tripping purposes. It has been common practice to use six-volt storage batteries for this purpose, but trouble is often encountered with such a low voltage, because of poor connections or worn contacts in the circuit. Twelve-volt batteries give less trouble of this sort, and are often used, but twenty-four volt batteries are recommended. A large part of the expense of such an installation is the cost of keeping the battery charged and, therefore, the extra expense of increasing the voltage from six volts to twenty-four volts is not a large percentage increase. Automobile batteries are probably the cheapest for this purpose and can readily be obtained. Where the battery can be charged only at rare intervals, it is suggested that special batteries of the type used in railway signaling be installed. Sometimes the battery can be arranged so that it will be kept charged by a trickle charger, and this practice is recommended. It is important to install a battery which will not freeze in severe weather and it is important also to test each circuit occasionally to see that it is in working order.

In most generating stations and larger substations, a 125-volt direct-current source is used for all control work. This source is usually maintained by a motor-generator set having a storage battery floating on the line in order to insure against any possible interruption. Most standard circuit breakers can be equipped with trip coils for any of the mentioned voltages.

### ALTERNATING-CURRENT SHUNT TRIPPING

Sometimes trip coils have been operated by alternating-current voltage but the trouble with such an arrangement is that their source of power is usually so closely associated with the circuits to be protected, that in case of a heavy short-circuit the voltage will be too low to operate the trip coil.

### SERIES TRIPPING

A common method of tripping is to use the ordinary alternating-current trip coil connected in series with the current transformer secondary, and normally to short-circuit this trip coil by means of contacts on the relay. When the relay operates it opens these contacts, and allows the current from the current transformers to flow through the trip coils and thus operate the circuit breaker. There are several objections to this method, one of them being that some protective relays are intended to operate when the current flowing through the trip coil is comparatively small and, therefore, insufficient to operate. Another objection to this arrangement is that heavy contacts are required and it is difficult to apply these contacts to relays having the required accuracy. It usually is demanded that the trip coil be capable of operating when the current is as low as five amperes, that is it should have an impedance of one ohm or more. On the other hand, a short-circuit may be so heavy that the current in the trip coil is limited only by the ability of the current transformer to supply it. Such short-circuit values through the trip coil may amount to 100 or 200 or even 300 amperes. It is necessary, therefore, for the relay contacts to be able to carry five amperes continuously without overheating and at the same time be able to withstand the opening of a circuit of approximately 300 amperes at 300 volts. Needless to say, no satisfactory relay has yet been designed for this service. Where conditions are such that tripping by means of the current transformers is demanded, a suitable transfer relay can be used, provided reasonable attention is given to keeping its contacts in proper operating condition.

Certain types of circuit breakers are furnished with a direct-trip attachment, an excellent device even though the name is somewhat misleading. Such circuit breakers are tripped by current from the current transformers, but the arrangement is such that sensitive relays can easily control the operation of the trip coils without injury to their contacts.

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# The Proportionality Chart

F. PAULSEN

IN a relationship of four variables, three of which are known for any given condition, the fourth can readily be found by means of the proportionality chart*. Such a chart is shown in Fig. 1 where, in the expression $a/x = y/z$, $x$, $y$ and $z$ are known and $a$ is to be determined. The co-ordinates $y$ and $z$ are inverted and a diagonal drawn from the corner where $a$ and $x$ have their origin to the corner where $y$ and $z$ have their origin. The scheme of operation consists of connecting known points on the $x$ and $z$ ordinates by a straight line, and from the known point on $y$ passing a straight line through $o$, the point

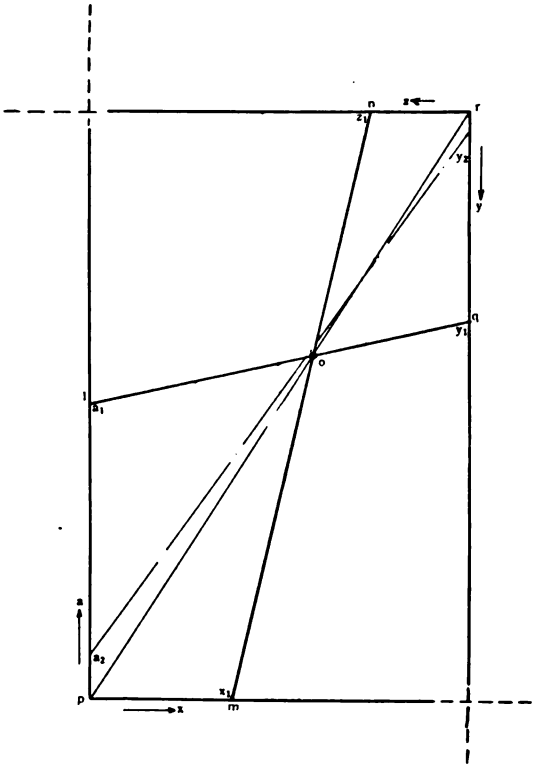


FIG. 1—A CHART FOR SOLVING THE EQUATION $A = XY/Z$, IN WHICH $X$, $Y$, AND $Z$ ARE KNOWN

on the diagonal where the line $x_1$ $z_1$ crosses, to a point on $a$ where the answer $a_1$ is found.

The proof of this chart is very simple and may be given as follows:—In Fig. 1 it will be noted that triangle $pol$ is similar to triangle $roq$ and triangle $pmo$ and $rno$ are similar. From this similarity the following relationships can be written:—

$$\frac{pl}{rq} = \frac{po}{ro} \text{ and } \frac{pm}{rn} = \frac{po}{ro}$$

From which we get,—

$$\frac{pl}{pm} = \frac{rq}{rn}$$

or,—

$$pl = \frac{pm \times rq}{rn}$$

Using the symbols of Fig. 1 this becomes,—

$$a = \frac{x \times y}{z}$$

which is the original equation.

A common expression of the form $a = (xy)/z$ is found in the formula for the strength of a rod or shaft in tension:—

$$M = (pI)/e$$

where, $M$ = moment in lb. in., $p$ = fibre stress in lbs. per sq. in., $I$ = moment of inertia of cross-section in in.$^4$, $e$ = distance from the neutral axis to the extreme fibre in inches.

A chart covering this expression can be made, letting each space equal one unit. However, we would find that the ranges this would give would not cover those found in practice, so that it is necessary to change the ordinates to come within

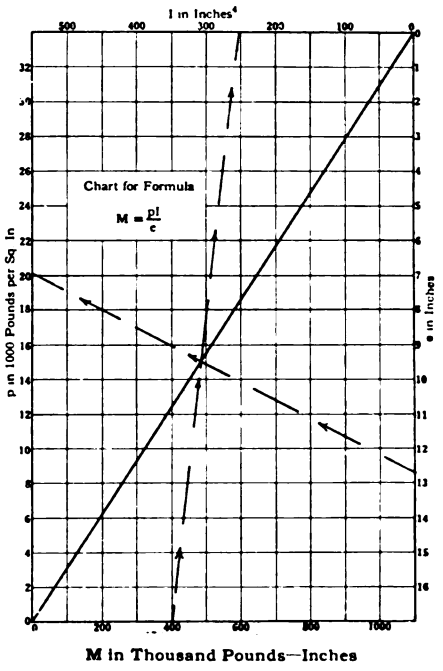
I in Inches⁴
500 400 300 200 100 0
Chart for Formula
M = pI/e
p in 1000 Pounds per Sq. In.
e in Inches
0 200 400 600 800 1000
M in Thousand Pounds—Inches

FIG. 2—A CHART FOR FINDING THE STRENGTH OF A ROD IN TORSION

limits usually involved. The chart as arranged for maximum convenience is shown in Fig. 2. The equation $M = (pI)/e$ is usually solved to find the value of $p$ and particularly to find whether or not the value of $p$ comes within the limit established for safety. Choosing $M$, $I$ and $e$ for the usual range of problems, the values of $p$ can be laid off accordingly. That is,

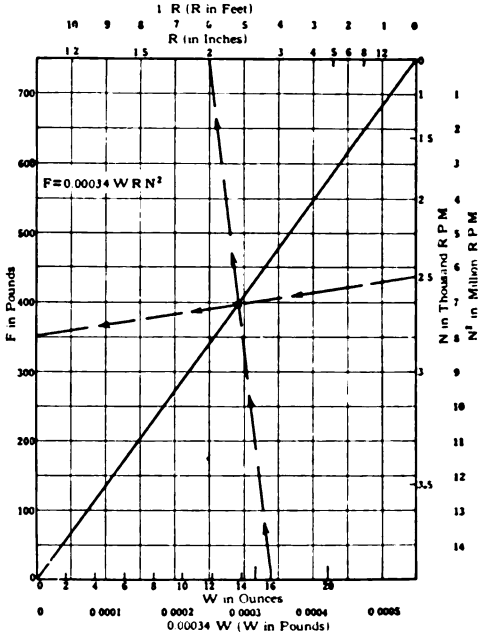


FIG. 3—A CHART FOR DETERMINING THE CENTRIFUGAL FORCE OF A REVOLVING MASS

it will be noted that one space gives a value of one for $e$ and a value of 50 for $I$. The ratio $I/e$ then is 50. Since $M/p = I/e$ then $M/p$ is 50, which gives a value of 2000 for one space of $p$, since one space of $M$ equals 100 000.

The form of equation may be changed for different problems. For instance, the question may be expressed as $a = ijk$.

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In such a case the equation for use on the chart is changed to $a = \frac{ij}{\frac{1}{k}}$ where the reciprocal values of $k$ are used. Each reciprocal value corresponds to a value of $k$ and by designating on the chart the reciprocals by their denominators, the chart is easily read. In other words, the values $1/k_1$, $1/k_2$, $1/k_3$, etc., are marked $k_1$, $k_2$, $k_3$, etc., for convenience. Another form of the equation may be $a = (i^2g)/m$. Here the squared values are laid off, but designated on the chart by the square root values—the values $i_1^2$, $i_2^2$, $i_3^2$ are marked $i_1$, $i_2$, $i_3$.

An equation involving these last two principles is found in the formula for centrifugal force:—

$$F = 0.000\,34\,WRN^2$$

where $F$ = centrifugal force in lbs., $W$ = weight of rotated mass in lbs., $R$ = radius to center of gravity of the mass in ft., $N$ = r.p.m. of the rotated mass.

Besides the reciprocal and the square values is added the constant, which will be treated together with W. The equation for use on a proportionality chart then becomes:—

$$F = \frac{(0.000\,34W)\,N^2)}{\frac{1}{R}}$$

and the chart is given by Fig. 3.

The chart is not limited to the boundaries given, but can be extended as shown by dotted lines in Fig. 1. A fault that is readily apparent in this type of chart is, that in determining point $O$, accuracy is greatly reduced when line $(a_1\ y_1)$ of Fig. 1 approaches parallelism with the diagonal. This is shown by the dot and dash lines of that figure. However, the scales can usually be arranged so that this condition is not apt to occur.

The chart will quickly give the answer to a problem with a fair degree of accuracy but its use is especially desirable in problems where the decimal point leads to exasperation, and where a ready check is wanted.

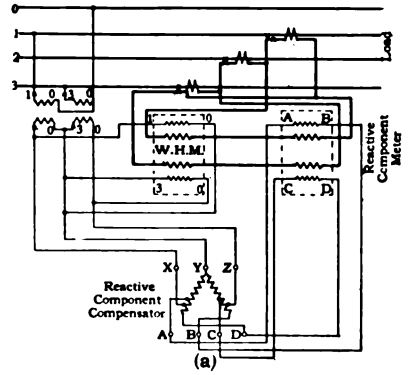
*For a complete study of this subject see "Graphical and Mechanical Computation" by Lipka, published by John Wiley and Sons, N. Y., and "The Construction of Graphical Charts" by Peddle, published by McGraw-Hill Book Company, N. Y.

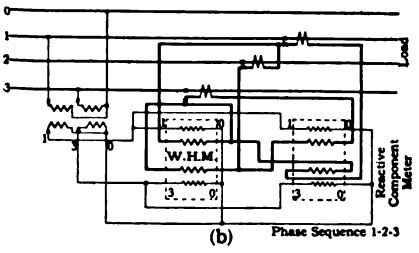
# The JOURNAL QUESTION BOX

Our subscribers are invited to use this department as a means of securing authentic information on electrical and mechanical subjects. Questions concerning general engineering theory or practice and questions regarding apparatus or materials desired for particular needs will be answered. Specific data regarding design or redesign of individual pieces of apparatus cannot be supplied through this department.

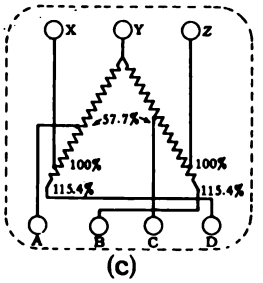
To receive prompt attention a self-addressed, stamped envelop should accompany each query. All data necessary for a complete understanding of the problem should be furnished. A personal reply is mailed to each questioner as soon as the necessary information is available; however, as each question is answered by an expert and checked by at least two others, a reasonable length of time should be allowed before expecting a reply.

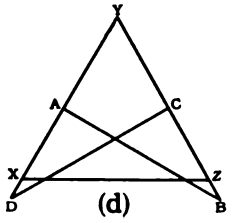
2845—REACTIVE WATTHOUR METERS—We are now metering several three-phase, four wire feeders with two element watthour meters using three current transformers in delta and two potential transformers connected line



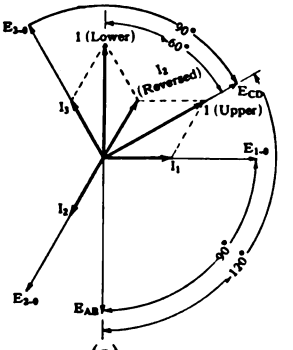

to neutral. We now wish to add reactive watthour meters. As we see it, there are two possible connections which should give accurate reading on balanced loads, but as to which connection will give the least error on unbalanced loads we are uncertain. Connection one is to use the same currents as in the kw-hr. meter and use a reactive component compensator to get voltage 90 degrees out of phase with those on the kw-hr meter. One voltage connection to the compensator would have to be reversed to give a 60 degree phase relation on the compensator coils. Connection 2 is to use the same po-

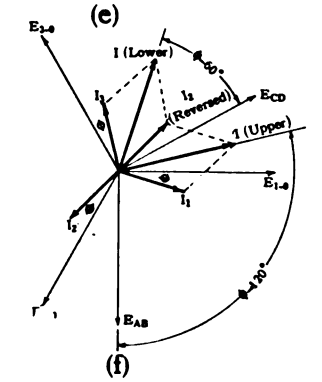



tentials as on the kw-hr meter, but use currents which are 90 degrees out of phase with the currents in that meter. To do this it would be necessary to use phase currents in the reactive meter and then close the delta for the kw-hr meter. The constant for this connection will be 1.73 times the constant on the kw-hr meter. Which of these two connections will give the most accurrate metering? Will you please give a wiring diagram for this? E. C. S. (TEXAS)

Of the two methods of measurement of reactive volt-ampere hours with




ordinary two-element watthour meters, Fig. a uses a reactive component compensator and Fig. b does not. The first method is the most accurate as it is independent of current unbalance al-

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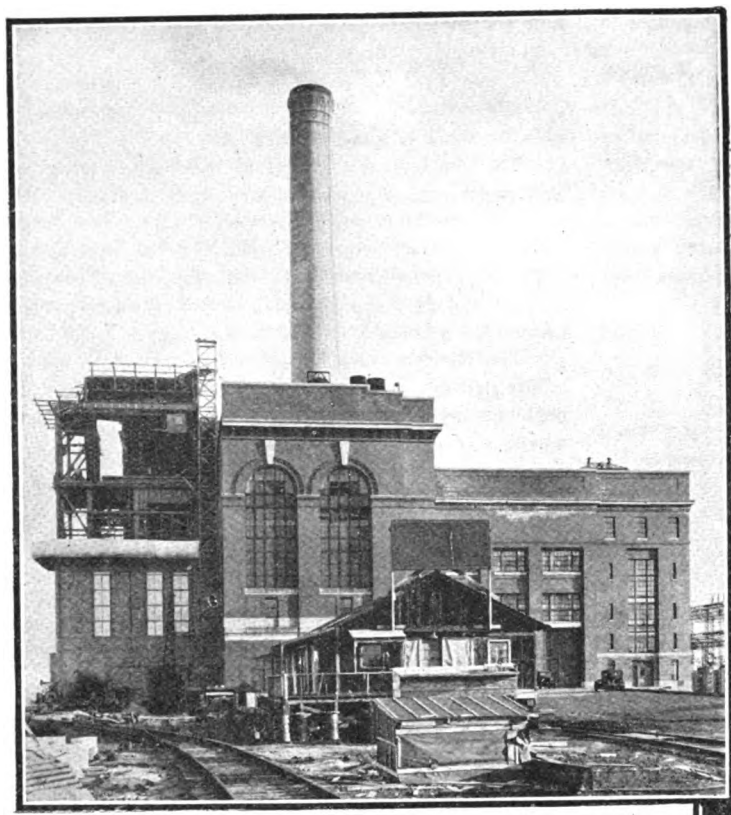
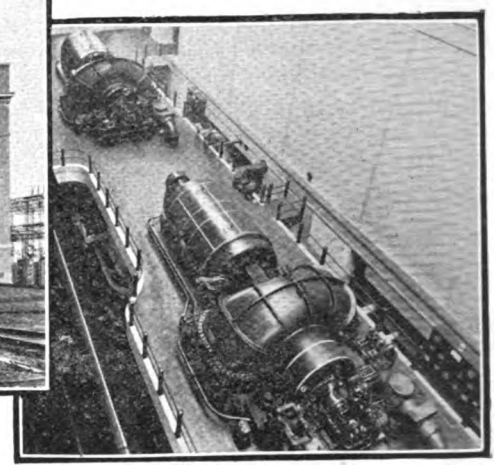


A recent photograph. The construction work is for a new Mercury boiler extension

Hartford Electric Light Co.
Hartford, Connecticut

Turbine Room



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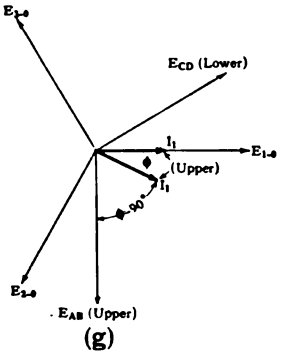
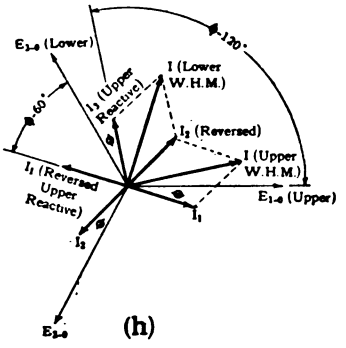
though not of voltage unbalance. The second is not independent of either current or voltage unbalance and is correct for balanced loads only. The measurement also requires a multiplying constant of 1.73. The explanation is as follows:—In Fig. (a) the corresponding current coils of the watthour meter and the reactive component meter are connected in series. The three current transformers have their secondaries connected in delta and are connected to the meters in the manner generally used for three-phase, four-wire system. The voltages impressed on the potential coils of the reactive meter are 90 degrees displaced from the corresponding voltages of the watthour meter, this displacement having been obtained by means of the reactive component compensator. The primaries



(g)



(h)

of the two potential transformers are connected from line to neutral in an incomplete Y, and the secondaries in an open delta. The delta connection is necessary in order to obtain the desired voltage relations for the compensator. The internal connections of the compensator are shown in Fig. c. It necessary that the voltage impressed on $YZ$ be 120 degrees from that impressed on $XY$. The polygon of vectors is shown on Fig. d. $E_{AB}$ is equal in value to $E_{XY}$ and lags by 90 degrees. Also $E_{CD}$ is equal to $E_Y$ and lags 90 degrees. These values and relations were obtained by the proper selection of taps on the windings of the compensator. Referring again to Fig. a, it will be seen that the voltage on $XY$ is $E_{1\text{-}0}$ and the voltage on $YZ$ is $E_{3\text{-}0}$, hence $A_{AB}$ lags $E_{1\text{-}0}$ 90 degrees, also $E_{CD}$ lags $E_{3\text{-}0}$ 90 degrees. Figs. e and f show the vector relations that exist in the reactive component meter when the load is unbalanced. Fig. e is for unity power-factor and Fig. f for any other power-factor, the currents being displaced from the unity power-factor position by an angle $\phi$. The voltage impressed on the potential coils of the upper and lower elements are $E_{AB}$ and $E_{CD}$ respectively. The current in the upper current coil is the vector sum of $I_1$ and $I_2$ reversed and has a value of 1.732 times that of either $I_1$ or $I_2$. In a similar manner the current in the lower current coil is made up of $I_3$ and $I_2$ reversed. At unity power-factor $I$ (upper) leads $E_{AB}$ 120 degrees or is displaced by an angle of —120 degrees. At any other power-factor it will be displaced by an angle ($\phi$ — 120). The upper element then measures,—$E_{AB}$ $I$ (upper) cos ($\phi$ — 120). As the system is balanced, the sub letters may be dropped and $\sqrt{3}\,I$ substitute for $I$ (upper) and we have

$$\sqrt{3}\,EI \cos(\phi - 120)$$
$$= \sqrt{3}\,EI\,(\cos\phi \cos 120 + \sin\phi \sin 120)$$
$$= \sqrt{3}\,EI\,(-0.5\cos\phi + (\sqrt{3}/2)\sin\phi)$$

In the lower element $I$ (lower) is displaced from $E_{CD}$ by — 60 degrees at unity power-factor, and $\phi$ — 60 at any other power-factor. The lower element measures,—

$$E_{CD}\,I \text{ (lower) } \cos(\phi - 60)$$
$$= \sqrt{3}\,EI \cos(\phi - 60)$$
$$= \sqrt{3}\,EI\,(\cos\phi \cos 60 + \sin\phi \sin 60)$$
$$= \sqrt{3}\,EI\,(0.5\cos\phi + (\sqrt{3}/2)\sin\phi)$$

Adding the two quantities measured by the upper and lower elements the cosine terms cancel out and the total reactive component is 3 $EI$ sin $\phi$. This is the expression for total reactive component in a three-phase, four-wire balanced system. The meter will also measure the reactive component correctly when the currents are unbalanced. Assume a single-phase load drawn from line 1 to neutral. This current $I_1$ will all pass through the upper element and at unity power-factor would be in phase with $E_{1\text{-}0}$ and 90 degrees out of phase with the voltage $E_{AB}$ on the upper potential coil, hence there would be no rotation of the meter. At any other power-factor $I_1$ will be displaced ($\phi$ — 90) degrees from $E_{AB}$ and the meter will measure, $EI$ cos ($\phi$ — 90) = $EI$ sin $\phi$. In a similar manner a single-phase load on any of the other phases or combination of single-phase loads would be measured correctly. Errors will be introduced if the voltages are unbalanced because the necessary 90 degree displacement of voltages in the compensator will be destroyed. An inspection of Fig. d would show this to be the case. However these errors are not serious unless the voltages are badly unbalanced. Next consider Fig. b. In this method no compensator is used and the voltages impressed on the reactive component meter are the same as those on the watthour meter. Current $I_2$ does not pass through the meter at all. Currents $I_1$ and $I_3$ pass through the meter before the delta is closed. By this arrangement it is possible to have the currents in the reactive component meter which are 90 degrees from the corresponding currents in the watthour meter. $I_3$ leads the current in the upper coil of the watthour meter by 90 degrees, so it is passed through the upper coil of the reactive meter. $I_1$ (reversed) leads the current in the lower coil of the watthour meter by 90 degrees, so it is passed through the lower coil of the reactive meter. In the upper element $I_3$ of Fig. h is displaced from $E_{1\text{-}0}$ by ($\phi$ — 120) degrees and this element measures $EI$ cos ($\phi$ — 120). In the lower element $I_1$ (reversed) is displaced ($\phi$ — 60) degrees from $E_{3\text{-}0}$ and this element measures $EI$ cos ($\phi$ — 60). If these two qualities are expanded and added the sum will be, 1.732 $EI$ sin $\phi$. But the total reactive component for a balanced three-phase, four-wire system is 3 $EI$ sin $\phi$, consequently it is necessary to multiply the above expression by 1.732 in order to obtain the correct result. As far as unbalanced currents are concerned, consider an extreme case of single-phase load drawn from line 2 to neutral. The meter would not register anything since the current $I_2$ does not pass through the meter. As voltage $E_{2\text{-}0}$ is not brought into the meter the measurement must necessarily be subjected to voltage errors but as voltages are seldom seriously unbalanced errors from this cause can usually be neglected. C. O.

2846—Autotransformer Phase Transformation—Fig. (a) shows two customer installations of Scott connected auto transformers. All transformers are designed for 4150 volts with taps. 1—Can three-phase, three-wire and two-phase, four-wire be taken from the two-phase bus with customer No. 1 connected as shown and with customer No. 2 disconnected, say three-phase power is desired at line $x$? If so will it be distorted? 2—If customer No. 2 wants to be given service will the transformer have to be phased out? If so, why? 3—With motor on customer No. 2 and a short comes on at points $y_1$, $y_2$, $y_3$ what will happen to the system? The motor was three-phase delta connected. I will want to use it star connected on 4150 volt with neutral grounded. 4—What will happen if a single-phase ground comes on at $y_a$, $y_b$, $y_c$, $y_d$? 5—What will happen if we take the neutral ground off the motor with the

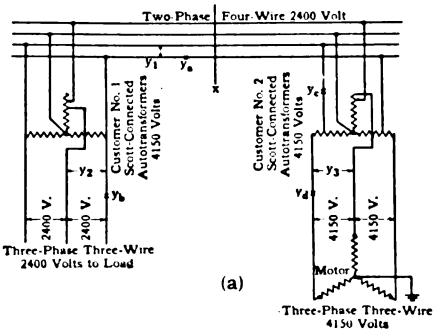



FIG. 2846

above conditions? 6—Will this motor operate satisfactory without the neutral grounded? 7—Will balanced or unbalanced load near customer No. 2 give telephone interference, with motor neutral grounded and ungrounded if this were a three-phase four-wire system? R. H. T. (N. J.)

1—Two-phase, four-wire power can be taken directly from ths bus, irrespective of customers 1 and 2, provided neither of these customer's connections introduce operating difficulties. Three-phase, three-wire service may be taken off at $x$ provided the proper phase transformation is arranged for at this point. I can see no reason for current or voltage distortion in this case. 2—It is always well with the complicated arrangement of this kind to phase out the connections to be sure that the proper conditions are established. 3—A short at $y_1$ will be the most serious as minimum impedance exists. A sufficient voltage may be absorbed in the short to badly unbalance the system. A short

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at $y_2$ or $y_3$ would be less serious due to the additional impedance in the circuit. 4—A ground at $y_a$ and $y_b$ will give substantially the same results ignoring the smaller capacity of lead $y_a$. The result of a ground on a system depends to a large degree on the other grounds which exist. If a star-connected motor with grounded neutral is used, a ground at $y_a$ or $y_b$ will short out one phase of the motor and resulting action will be practically equivalent to a short-circuit. A ground at $y_c$ or $y_a$ will give substantially the same results if the motor neutral is grounded. 5—If the neutral ground is removed from the motor the main bad results will disappear, particularly if there are no other grounds on the system. 6—The motor should operate satisfactory with the neutral ungrounded aside from the high pressure to ground which would result from an accidental ground on the motor terminal. 7—Conditions in the three-phase system which will permit high harmonic currents to flow in the line will give the telephone disturbances. Such currents will flow when a neutral of the circuit is grounded, if the neutral of the generator is also grounded. E. G. R.

2847—ANGULAR DISPLACEMENT OF WINDINGS OF DOUBLE PRIMARY TRANSFORMER—Will you kindly answer the following questions concerning Fig. (a). 1—What will be the angular phase displacement of windings *A* and *B* at no load on either of them? 2—What will be the angular phase displacement if the secondary is loaded and there is no load on the tertiary? 3—Will this difference of phase displacement, if any, effect the synchronizing of this bank? 4—Where would be the best location of potential transformers for synchronizing? H. D. C. (N. Y.)

Fig. (a) shows a three-winding transformer with the 6900 volt secondary connected to a line. One of the 13 200 volt windings is connected directly to a generator. The other 13 200 volt

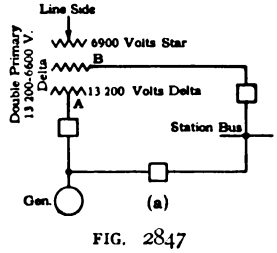


FIG. 2847

winding is connected in parallel with the first and the station bus is taken from the junction of the two. With no load on either winding *A* or *B*, the voltage of the two will be either in phase or 180 degrees out of phase, depending on the way the leads are arranged. This assumes that both windings are connected in delta. If the windings are 180 degrees out of phase they can be brought into phase by the interchange of the leads from one transformer. When lead is put on winding *A* or *B* separately, there is a tendency for the two voltages to assume a slight angular position with regard to each other. This is due to slightly different characteristics of the two windings. The windings may not have the same resistance, and due to their relative position, the magnetic leakage with regard to the third winding may not be the same. With these characteristics differing they will not respond the same to the load, particularly if the power-factors of the loads on the two windings differ. If, however, the two windings are put in parallel, the two voltages are forceably brought into phase with each other. The agency which does this is the division of the load in the two windings. This is, in effect, a circulating current between the two windings. There will be no difficulty, therefore, in paralleling or synchronizing the windings. Synchronizing is not really necessary unless the windings are connected to different sources of power. E. G. R.

2848—"A" ELIMINATOR—I would like to ask a few questions about building an "A" elminator. I am using a Tungar battery charger as rectifying unit, with a standard 6 volt storage battery floating across the line as an electrolytic condenser. The rest of the filter consists of the primary of a home-built 100-watt transformer, in series with the line to the radio set. This gives excellent results, except for an IR drop across the choke that is a little larger than is desirable. I wish to replace the 6-volt battery with something that will perform as well, with a higher terminal voltage, giving me a true eliminator. Now come the following questions:—1—a higher-voltage, lower ampere-hour capacity battery should do the trick. How low in capacity would it be safe to go without injuring the cells through excessive continued charge and discharge? If a 10-volt bank of storage B cells, such as (a) the Williard, 1.5 in. by 6 in., or (b) Edison-type ¾ in. by 6 in., were used, how many such banks would need to be put in parallel to obtain sufficient current capacity and condenser capacitance for the eliminator, assuming a 12-volt, 2-ampere rectifier output? 2—If, as you suggest, dry batteries were to be used, would a standard C-battery block of 10-volt size, give sufficient current capacity and condenser capacitance? 3—Would a single cell of the aluminum—lead variety (electrolytic condenser) be satisfactory, with an aluminum area of 6 sq. in. 4—If I "form" the plates of the cell on 110 volts, alternating current, will the film thus formed remain unchanged when the cell is put in use on 12-volts direct current? Or might it be desirable to form the plates at voltage other than 110? F. W. B. (MICH.)

1—Any standard storage battery should be able to carry the ripple current from the rectifier without injury. (b) One bank should be sufficient. 2—The standard C battery block should give sufficient capacity for many months. After it is old it may begin to prove inadequate. 3—A single aluminum cell of the dimensioons given would not be satisfactory. 4—After forming the plates at 110 volts, the film will gradually reduce in thickness after it is left in the electrolyte with 12 volts. I would recommend forming the plates at 12 volts. J. S.

2849—INVERTING A SYNCHRONOUS CONVERTER—A manufacturing plant is equipped with direct-current and alternating-current motors. The direct-current motors and some of the lights are supplied from two 110 kw, 250 volt, three-wire generators, gas-engine driven. The 440 volts alternating-current motors and the remaining lights receive their supply from the local public utility, which also supplies power to operate a 200 kw, 250 volts, 800 amperes, 1200 r.p.m., six-phase, synchronous converter which is run in case the two direct-current generators are shut down. It is desired to run this converter inverted, that is, to supply alternating current for the alternating-current motors and lights, by supplying it with direct-current from the gas-engine driven units. Can this be done satisfactorily? Will it be necessary to provide a starting rheostat for the direct-current end of the converter? Would separate excitation of the shunt field make its operation more stable? Would it be preferable to cut out the series field of the converter or reverse it? The converter is provided with an overspeed device. Please explain fully all steps necessary. P. J. (OHIO)

It is possible to operate a synchronous converter inverted satisfactorily providing some slight frequency variation is not objectionable and providing rather close supervision is available. If the converter when operating inverted is started from the direct-current end, it will be necessary to supply normal field excitation to its shunt fields and apply a reduced voltage to its armature during starting. This reduced voltage can be obtained either by means of a starting resistance in the armature circuit or by connecting the converter to one of the gas-engine-driven generators, whose field should be separately excited and whose voltage can be gradually raised from the residual to its rated voltage, thus bringing up the speed of the converter to normal, as the voltage of the generator is raised. In this case separate excitation from the other gas-engine-driven generator can be used. A simpler method of starting would be to start the converter from the alternating-current end as is now done, then to parallel the direct-current end with the two gas-engine-driven generators and then disconnect the alternating-current supply from the load, thus causing the converter to run inverted. In any case, when a compound-wound synchronous converter is operated inverted, the series field should be reversed so as to give a cumulatively compounding action from the series field. The shunt field of the converter should not only be separately excited, but it should be excited from an exciter direct connected or belted to the converter shaft. This exciter should be self-excited, and should not have its magnetic circuit saturated, so that if for any reason, such as the demagnetizing action caused by an induction motor load on the converter, the converter would tend to speed up, the increased speed on the converter exciter would raise its voltage and thus strengthen the field of the converter and keep it from running away. C. L.

## CORRECTION

In the article, How to Obtain Current and Voltage in Phase from a Three Phase, Three-Wire System, p. 367 of the July JOURNAL the last line of the first paragraph should read "$E_{ac}$ but has a magnitude of 1.73 times line current" and the third line of the last paragraph should read "to use 1.73 times line current and line voltage. Thus the"

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# THE ELECTRIC JOURNAL

VOL. XXV SEPTEMBER, 1928 NO. 9

## The Lure of the Difficult

The most dynamic urge in life is the struggle for supremacy; a struggle which lies at the root of competition, individual as well as that of corporate enterprise. There is a rare flavor of satisfaction in being the master of men, materials and forces, or knowledge. Mentality is focused, imagination is directed, toward the achievement of creative enterprises, because there is in human nature a demand for endeavor.

The engineering accomplishments of the last half century are a vast tribute to the constructive resourcefulness with which the technical mind has become armed. And yet, these accomplishments have resulted from the work of a relatively small number of men possessed of leadership and imagination. True, every man cannot be a genius in his chosen field, but there can be a steadier aim toward the ultimate in the design and application of mechanistic structures. The keen insight which makes such a concentration of purpose possible results from an understanding of the laws of natural science. If the engineer is open to criticism, it must be on the ground that he does not work fundamentally enough. It is difficult to think basically, peculiarly difficult where electrical phenomena are involved. Unguided experimentation rather than careful analysis, an overly-emphasized reliance on the generalized facts gleaned from experience, weigh too heavily in development and design. It is necessary to attempt to perfect theoretical knowledge because of the awkwardness inherent in attempting to carry over past experience into dissimilar problems.

Too often the accepted rudiments of a good design must be completely reversed in the light of a later and better understanding. A large part, though not all, of the resultant lost motion in the building of machines could be eliminated by more fundamental engineering thought. The profession should apologize for having at times overcome the difficulties which arise in a new development by adding relay to relay or coil to coil rather than by employing more applicable principles. The simplest combinations of devices are usually most satisfactory—though often most difficult to attain.

Scientific truth is fascinating because it lights the way to momentous possibilities. There are men whose developments have been outstanding, and who have attained them exclusively through fundamental study. One example of such a development is the autovalve lightning arrester, conceived by applying the fundamental principles of the conduction of electricity through gases.

The opportunity to revel in analytical investigation is ever present; and for the engineer, no urge is more interesting nor more directly fruitful. There are too few masters, men who have reached the pinnacles of technical success largely because of the lure of the difficult.

LEON R. LUDWIG

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## Economic Principles of Design

A broad consideration of the economics of design begins with the first piece of material and the first manufacturing operation considered by the designer, and runs through the history of the apparatus until it has been finally junked and sold as raw material, from which a new designer will build a new machine to meet a new set of economic conditions.

In general, the result of a study of economic conditions should be reduced factory cost of apparatus. By the term factory cost is meant the sum of three elements—labor, material and indirect factory expense. The third term is sometimes called overhead, and includes such items as supervision, light and heat, depreciation of tools and similar expenses.

The fundamental separation into labor and material immediately introduces an economic question as to where to balance labor savings at the expense of material, and vice versa. An example of this might be a casting made heavy to minimize molding labor, or hand layout operations permitted on pieces with limited production to save the cost and investment in jigs and fixtures.

Before the design of the apparatus is begun, some more general problems of an economic nature suggest themselves.

*Operating Problems*—From the users' point of view two important considerations are investment and power cost. The first of these is not so innocent as it might appear. A contract for 25 000 kw in transformers was awarded to the successful bidder because he guaranteed 99.4 per cent efficiency as against his competitor's 99.3 per cent. The additional 0.1 percent losses were iron losses, and were capitalized at $200 per kilowatt, which amounted to a

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total of $5 000 or in the neighborhood of 15 percent of the price of the job. On the same basis of consideration copper losses are capitalized at $100 per kw. This means that a penalty of 0.75 percent in iron losses amounts to the entire selling price of the machine and a 1.5 percent lower efficiency due to copper losses would have the same result.

*Selling Problems*—Almost all economic problems are selling problems in the end, but some have a direct bearing. For example, how strong a selling argument is quality; and how much better performance or longer life or more satisfactory operation can the designer afford to put into his apparatus and still meet a market price set by cheaper and less responsible competition? A part of this depends on the ability of the commercial department to convince the purchaser that these additional values actually exist, and that economically he is justified in paying a higher price to secure them.

*Engineering and Manufacturing Problems*—At every turn, the designing engineer finds himself face to face with the necessity of designing apparatus which can be built at a cost, sold at a profit and which will give satisfaction and life in service. This involves initially an economic organization. Taking this for granted, a good idea of the economic problems from that point on can be obtained by considering some of the things which come up when a new line of machine is to be put into production. Let us say, a successful line of squirrel-cage induction motors has been on the market for a number of years, the mechanical parts of which were iron castings, the squirrel-cage rotor bars were bolted to the short-circuiting rings and the laminations of the stator core were punched in a one-piece annual ring. The stator slots were open and the windings were arranged in the well-known diamond coil form, with two coil sides per slot.

Let us assume that the art and competition had advanced to a point where this line of motors, while eminently satisfactory in mechanical operation, long life and minimum repairs, no longer had high enough efficiency and power-factor, and contained too much material and labor to be sold at a reasonable margin of profit. What then are the economic pros and cons? Some of them are like this; cheaper mechanical parts can be made on certain ratings by changing from castings to members of pressed steel. This change involves heavy presses and expensive dies to produce the parts. Where is there a shop which can house the necessary equipment, and is it in a locality where labor of the proper training can be hired to do the work? Will the volume of production be great enough on these ratings to justify the original cost and interest on the investment for the tools which are required? How expensive will it be to overcome the established use of castings for this purpose and to educate the market to the advantages of pressed steel? Will such a line of mechanical parts yield itself as readily to the assembly of machines with special features, such as vertical shaft, back-geared, enclosed, etc., as do castings? How will the question of renewal parts on the old line be taken care of? Will it be necessary to provide storage space indefinitely for all the old patterns and formers, jigs and fixtures for the old line as well as the new, or is there some hope that repair parts for the old line might be made from the tools for the new? Is there some better way of forming and insulating the coils?

Thinking next of the power-factor and efficiency, the designer can improve these materially and also cut down the material in the machines by reducing the air-gap and also by making the stator slots partly closed instead of open. But there is a strong prejudice against small air-gaps and a stronger prejudice against windings in closed slots. So a careful economic balance must be made of sales resistance on one hand, and improved performance and reduced cost on the other.

Next comes a careful study of sizes of wire and rectangular conductors to be used for winding the coils of the complete line. The fewer sizes of special conductors that are used the less will be the stock to be carried, and probably also the lower the cost per pound. Also a study must be made of bolts and screws and drills and taps to be used, so that one size can be used throughout a machine as far as possible.

When it comes to the actual design, numbers of slots must be chosen which will cover the greatest possible number of phases multiplied by poles, because requests will be received for motors with special speeds, which must be built on the same punchings. The sizes of shaft extensions and keyways must be chosen to fit the maximum number of conditions. Possibly a gain could be made by using segmental punching; which would overcome the inherent disadvantages of the complete circle. Many problems of this nature, all involving economic considerations, could be quoted, even introducing the human element, such as designing so that women could be used in various operations instead of men.

Assuming that design and tooling questions are settled, inspection and testing specifications must be written so as to catch imperfect work without throwing out parts on technicalities which really do not affect quality.

All of these questions involve an immense amount of common sense and judgment to insure the happy general result of a contended user and a satisfied stockholder. That is why a designing engineer, if he weathers the storm and assimilates his experience, develops into an executive. It is because he has been finding in less degree the answer to a host of economic questions which *in toto* are the executive's responsibility.

A. M. DUDLEY

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# The Development of the Electric Arc Welding Process

**A. R. ALLARD**
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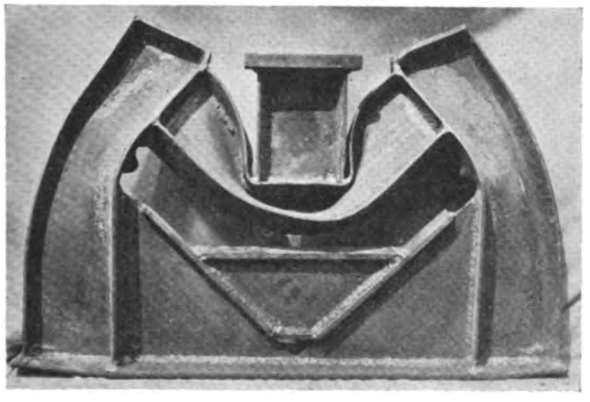
IN these days of accomplishment by both science and invention we are being surprised by startling achievements with such regularity and frequency as to tend to blur the perceptions to equally important developments in equipment, processes and methods which are the result of slowly acquired knowledge and painstaking investigation. Our perceptions are also somewhat dulled by the regular announcement of inventions or innovations of a spectacular nature which are often of greater news or advertising value than utility.

The slow evolutionary development of one familiar process has been gradually going on for the better part of the last two decades without attracting more than passing notice. At this time the evolution has attained such gigantic importance as to amount to an industrial process revolution—a revolution in the art of joining metals. Those who have not been in touch with the growth of electric arc-welding have suddenly discovered an unsuspected giant in their midst. During the last few years this new-old industrial giant has attained the prominence of front page headlines and the distinction of the pictorial section. This has not, however, entirely convinced all the intelligent, matter-of-fact conservatives of the superiority of the process of arc-welding, even though it is at times described by



AN ARC WELDED TEST STRUCTURE AFTER TESTING

lurid and intriguing word pictures. This is not surprising in view of the fact that many engaged in lines directly affected by the prowess of the invading giant look upon the present accomplishments, such as are shown in the accompanying illustrations, merely as experiments. Nothing could be farther from the actual fact. Arc-welding and the joining of fabricated structures by arc-welding are here to stay.

The fabrication of structures such as are shown in the illustrations is not stunt welding, nor is it part of an attempt to sell arc-welding equipment. It is the result of a long period of research which has culminated in the establishment of the fundamental facts of the process, as well as a knowledge of the possibilities and limitations of the process as it is carried out today.

The growth of this knowledge of the process of arc-welding has been slow, like the proverbial grinding of the mills of the gods. The grist produced has, however, been not unlike that produced by the mills of the gods in that it too has been exceedingly fine.

All along the line of its development, arc-welding has been continually under the most critical and exacting observation and tests. It has survived the over-optimistic efforts of its protagonists, as well as the attacks of its antagonists. Only worth and merit could have survived the opposition, unfair restraint and biased condemnation with which it was continually beset at every forward step of its evolutionary growth.

The young industrial giant, electric arc-welding, sits today securely enthroned as a major process in the art of joining metals. This security is based upon a foundation of knowledge of the fundamental principles and laws which apply to every phase of the process application. The giant has grown in power only as rapidly as we have accumulated knowledge of these fundamentals, and future growth in power will be in direct proportion to the accumulation of that knowledge. "Knowledge is power", and because of this, arc-welding has risen from obscurity to prominence and importance.

In the use of many industrial processes—and arc-welding is no exception—we have had to learn, as in real life, to creep before we could walk. In its infancy or creeping stage, arc-welding was first done

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with the carbon arc. By means of this process surface defects, which merely marred the appearance of steel castings, could be repaired; and occasionally two parts were joined by fusing them together. Later developments gave the modification of this process known as metallic arc-welding. It was the development of this process that made the structures shown in the illustrations possible.

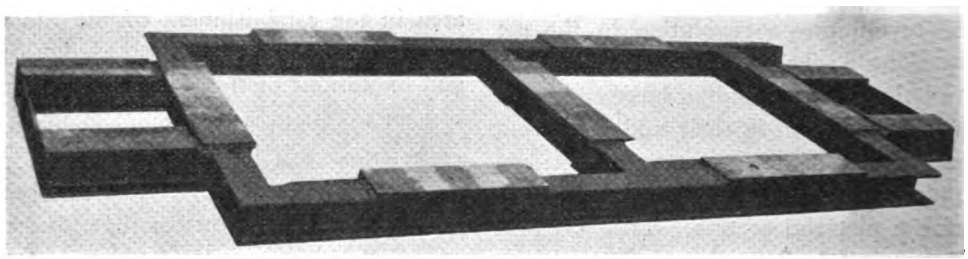
In the beginning any source of direct current available was used to do welding. The facilities for current regulation often consisting of nothing more elaborate than a water rheostat of home manufacture. In many cases the current regulation was seriously interferred with by other loads on the same line. In the light of this and other conditions known to have existed, it would seem at this distance that the good welds were the accidental ones.

Because of the fact that Norway iron had proven its worth as a material for welding purposes with other processes, and because it really did work a little better than other filler wire material then available, it was adopted quite generally as the right welding wire to use in making metallic arc-welds. After a time, and with better results than we would predict today in the light of our increased knowledge of the requirements for making a good arc-weld, various operators of an inquiring turn of mind began a haphazard investigation or trial of other kinds of wire. At times very good results were obtained by using cold-rolled steel, telegraph wire and hoops from barrels. These all had their champions who relied on them for the execution of their most difficult welds. Line fences, which were rapidly coming into popularity at the time, lost a lot of their attractiveness as well as effectiveness if it became known that the material could be counted on to make a good arc-weld. Practically all the wire available gave very uneven fusion and melted in such a way as to deposit the filler material in large globules.

The subject of fusion in arc-welding began to attract the interest of the welder and sometimes his superior. Facts which stood out more prominently than others began to take shape and were gradually crystallized into principles. For instance, it was found that any and all wire worked better with the correct arc length. It was discovered also, that molten filler material deposited onto cold parent metal did not result in a weld. After a time there was formulated the most important principle of electric arc-welding. This is that the molten pool in the parent metal must be carried along continuously without a break, and the electrode manipulation must be such that the molten filler material will be deposited only in this molten pool or arc crater.

After the discovery of these, and a few other principles, good arc-welds were secured when the other conditions, such as cleanliness, correct preparation, good wire and reasonable regulation of current, all occurred at the same time. As a result of these better welds, confidence increased in the process and it began to emerge from the creeping stage to the learning, or what might be called boyhood stage. Odd jobs began to gravitate to the arc-welding booth with more frequency and regularity. Important repairs, and castings with defects or alterations requiring welding for strength, began to be successfully done by the arc process.

At about this stage of the development of the process, the electrical manufacturing companies began to take the development seriously, and because of the fact that they had at hand the facilities for investigation and development on a scientific basis, they rapidly became the leaders in the process application. Investigation of the process by the research engineers resulted in the gradual accumulation of fundamental facts and principles, and the elimination of the haphazard and trust-to-luck methods of application and manipulation which had prevailed.



A MOTOR-GENERATOR BEDPLATE BUILT OF STRUCTURAL STEEL ARC WELDED

One of the greatest boons to the process resulting from these investigations was the correction of the faulty current supply by the development of generators designed especially for welding service. After extensive experimenting and investigation, the fact was established that generators of the constant-current type gave excellent results in the design of single-operator welding outfits; and that generators of the multiple-operator type could be wound in such a way as to insure positively that there would be no interference between operators, unless the generator was operated far beyond its rated capacity.

In addition to determining the best means of current regulation and the best types of generator windings, and analyzing current stabilization by means of reactance coils, etc., exhaustive tests were made to determine other necessary characteristics of a good welding generator. These efforts resulted in means of arc length control, ease of starting or striking the arc.

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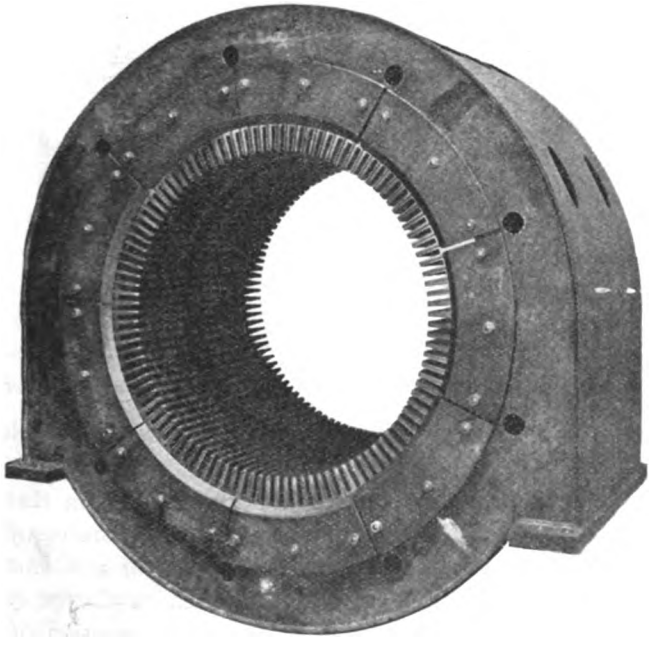
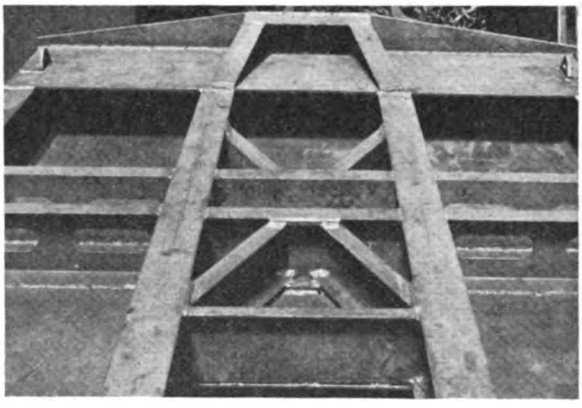
stability or tenacity in continuous operation as long as approximately the right length arc is held, and the characteristic of developing a hot arc terminal in the parent metal, or what is known as penetration.

The next important development in connection with metallic arc welding was the production of a satisfactory welding wire and the formulation of the requirements which a good wire should meet. It was found that a mild steel of certain approximate analysis was the most satisfactory arc-welding wire for general welding work. It was also found that the wire must have the characteristic of concentrating the arc terminal at the face of the wire end; and that the rate of fusion or consumption should be constant. This was found necessary in order to concentrate the arc terminal properly in the parent metal, as well as at the wire terminal, and to avoid the deposition of large globules of metal at one time from the electrode filler rod. Concentration of the arc terminal in the parent metal was found to be necessary in order to secure the necessary penetration and to provide the necessary fused or molten pool in which to deposit the filler rod material. It was also found necessary to require that the welding wire deposit a material of dense structure without porosity, blow holes or slag inclusions.

In an effort to produce a wire of this kind, many manufacturers entered the field and there was soon available wire in rolls, bundles and boxes, some of which was coated, some covered, some fluxed and some bare. It was all advertised to be the last word in welding wire. For a long time there was really only one maker of a truly good wire. Other makers flourished because of the fact that a standard of comparison was lacking. Few operators and far fewer supervisors knew just what to expect of a wire. After a time, however, the better wires became more favorably known and even better wires were produced. In addition to this, the American Welding Society, after considerable research, did a very commendable piece of constructive work by establishing standard specifications for the welding wire.



A TYPICAL ALL WELDED MOTOR STATOR
All parts except the laminations and finger plates were made from standard structural parts.



THE UNDER FRAME CONSTRUCTION OF AN ALL WELDED ELECTRIC LOCOMOTIVE CAB

The more skillful operators soon proved the advantages to be gained with the new generators and better welding wire by the frequency which they executed welds in the vertical and overhead horizontal planes. Welding of this kind never could have been done on a commercial basis without these developments.

The railway shops were perhaps the leaders in taking advantage of the process at this stage of its development. A few of the more progressive led the way. Others followed and still others lacked the initiative or confidence to apply the process to making maximum economies.

While the developments in generators, wire, etc., were being made, other engineers with the aid of the most expert operators, were formulating definite principles of welding procedure, manipulation and process application.

At about this stage, which might well be called the age of youth in electric arc-welding, we were plunged into the great World War. No youth, of all those enlisted, entered the service with more enthusiasm, and no more spectacular or crushing victory was won than that won by arc-welding in the repair of the purposely damaged, interned enemy vessels which lay in our ports. It was the intention to damage these vessels to such an extent that they would be out of service for at least a year. By use of electric arc-welding they were put in transport service in the incredibly short time of a few months.

The exigency of war necessities did more to place arc-welding on its relatively proper plane than possibly any other agency. In an effort to keep their motive power in service, railroad officials who had been previously antagonistic toward the application of the process began to look upon it with favor, and before long many became enthusiastic converts to the new process. Among other things, tires, driving boxes, couplers, switches and most important of all, boiler repairs and

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the welding of flues became standard practice. This latter has probably saved the railway companies more money than any other operation or process development of the last two decades.

The work done by the Navy Department and the various ship-building companies in the application of the electric arc to ship construction is another outstanding pioneering accomplishment.

The fabrication of all sorts of steel structures by use of the electric arc received greater impetus during the war than even its most enthusiastic promotor would have had the courage to predict. Many manufacturers rushed to the use of the process with little or no experience or knowledge of the fundamental principles involved. It was not surprising that some were over enthusiastic, and that their results were comparable with the amount of knowledge and experience invested.

This increased interest in the arc-welding process brought about a correspondingly increased activity along investigation and research lines. This in turn resulted in the accumulation of additional knowledge which led to a wider application of the process in the industrial field, and brought arc welding into what we may term its manhood. This advance was greatly aided by the strides which had been made during the war period in the field of training operators so as to fit them properly to observe and apply the fundamental principles of the process.

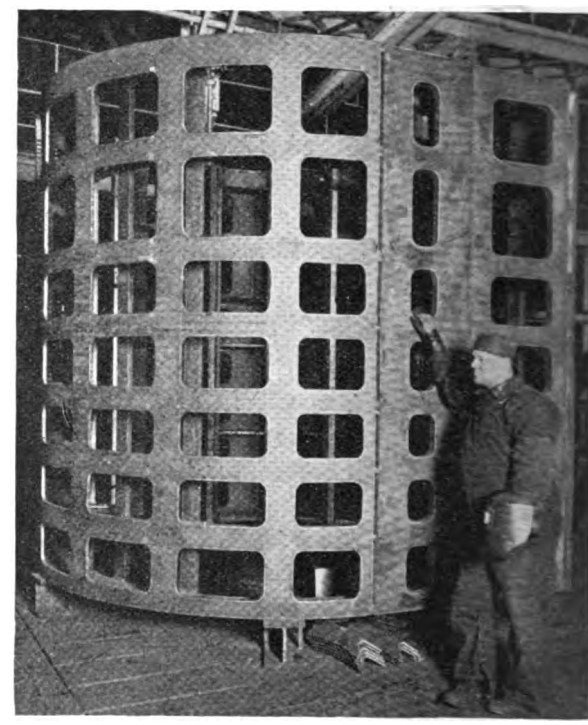
This period in the history of arc-welding was really that of another war, a war of attrition between processes of production. On the basis of the accumulated knowledge of the process, arc-welding now contested with the rivet, the bolt, the screw and with the other more expensive processes of welding or joining metals. By right of the conquests made during this period, arc-welding lay claim to the joining of the metal of the greater percentage of all steel tanks, containers, pressure vessels and fabricated structures other than buildings and bridges.

Investigation, research and improvements of the generator, the wire and the process application and training methods for both operators and supervisors continued throughout this period until the accumulated information or knowledge of the process began to approach more nearly the state of an exact science. This ushered in the present stage or the age of the giant. It might well be called "the engineering age in electric arc-welding".

Standards have been established by which structures can be designed for welding. The strength of weld metal is known for any particular stress application. Welded structures need no longer be precariously designed because of lack of information. Accurate control of the process application can now be accomplished, thanks to standardized practices and the formulation of the principles of preparation, procedure, manipulation and inspection.

The necessary knowledge is available for the use of the designer, supervisor, inspector, instructor and the operator. This knowledge has grown from that conveyed from operator to operator by word of mouth, to many volumes of useful, exact information. With this knowledge there have been designed and built pressure vessels and containers, many large buildings, several railway bridges, many miles of welded pipe lines and last but not least, the many and varied fabricated structures to be used as machine frames, bases and parts.

The use of fabricated machine structures offers the designer the opportunity to proportion the sections or members of a machine to the exact dimensions necessary to perform the functions for which they are intended. Due to the limitations of the casting process this has never been possible before. In addition to this, members of a structure can be so proportioned and located as to have the stresses transmitted to other



A TURBOGENERATOR FRAME DURING THE PROCESS OF FABRICATION

parts of the structure, thus dividing the load to which a member need be subjected.

These structures offer another advantage in that changes or variations from standard can be more easily and rapidly made. These changes consist of additions to or omissions from the standard, such as change in location of parts, change in foot height, omission of exciter supports, addition of brackets or pads on which to mount auxiliary equipment, and changes which might be found necessary in the field.

Fabricated structures occupy less space than cast structures and are of less weight. These features are of considerable importance in making shipment and in handling and installation. The rating of machines of a particular type which can now be built, tested or shipped assembled has taken a considerable jump. It

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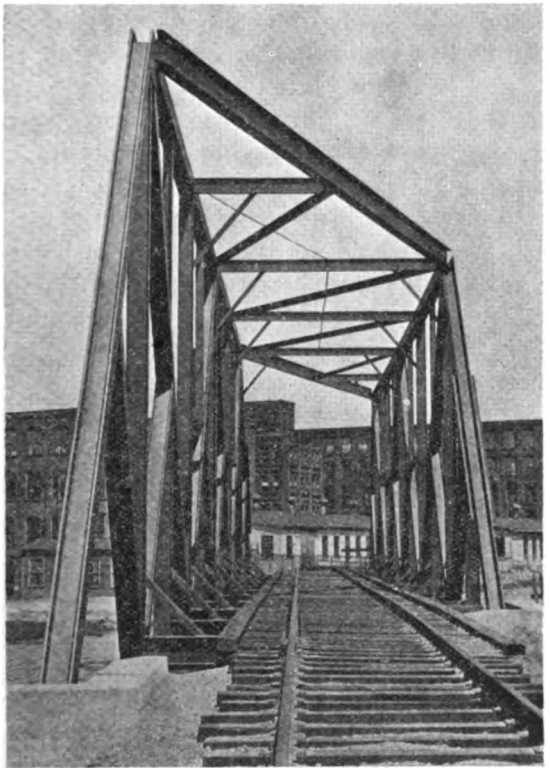
is not hard to visualize the extent to which the fabricated structure can be adapted, in meeting conditions which require that the particular machine be built in sections having a maximum fixed permissible weight on account of limited transportation facilities in remote places. The weight factor is also often a major consideration where there are building or foundation limitations.

The ability to make and keep shorter delivery dates and thus render to the customer the best possible service is sufficient reason without any other for



AN ALL ARC-WELDED RAILWAY BRIDGE BUILT TO CARRY HEAVY FREIGHT TRAFFIC

changing from cast to the fabricated structure. In these days the ability to deliver the goods enters into most all contracts.

From the standpoint of design features, the customer who buys the new fabricated machines gets all the better of it, and it is the designers delight to give it to him. When a line of machines is changed from the cast to the fabricated construction, an opportunity is had to incorporate the very latest discoveries and the best known engineering practice. All those points which have been considered for improvement and development are taken care of at the time the design is revamped. Special consideration is also given to such features as the incorporation of the latest and best practice in ventilation and lubrication. Bearing sizes and bearing design, about which much has been learned in recent times, are given special attention. Provision for balancing rotating parts is given more thought today than ever before, and the fabrication of rotating parts offers an opportunity to meet the newer and more exacting demands.

Up to the present time, electric arc-welding has not been hard pressed to meet any great public demand because it has had to supplant other highly developed methods of joining metals. The gains made by arc-welding have been made on merit and at the expense of some other method. Every gain registered was the result of a successful attack on inertia and at times on unreasonable prejudice. This is the opposite of the reception accorded such developments as the radio, the auto and the airplane. With welding the converts were made in the reverse direction. First there was the operator who could weld anything, IF..... His supervisor next came under the spell, and he in turn proceeded to co-operate with the engineer, who was at first skeptical, but willing to be shown.. It is to the everlasting credit of the engineer that he not only developed the facilities and the process, but sold the process to the managing executives. It is characteristic of these men that they made their decision to adopt a program of welding, even after due consideration of the metallurgists' reports that under the microscope they had been able to detect the horrible nitride needles, and that laboratory tests had revealed only a small degree of ductility or malleability. The orders given required only that the applications be kept within bounds of the exact knowledge of the process. This has been done. Nothing has been left to guess work and nothing need be to secure the full benefits of the process. We need only be guided by the accumulated knowledge which is available. That there are limitations to the application of the process in a wholesale and haphazard manner, goes without question. To refuse to make sensible use of a material or process merely because it does not measure one-hundred percent in every detail would be about as sensible as incarcerating a man because he happened to bruise his finger.

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# Waste--Its Prevention and the Freeing of Frozen Assets*

T. H. OWENS
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THE prevention of waste and the freeing of frozen assets is of vital concern to everyone, because the problem is encountered all the way from the production of raw materials, to the user or consumer, who may be a manufacturing, transportation or other industry, or an individual in business, or in the home. To analyze this problem intelligently, it is necessary first to determine what is waste and what are frozen assets. Waste and frozen assets being practically synonymous, the definition of the former will serve to cover the latter as well.

The standard definitions of waste are: lying unused, unproductive, worthless, refuse; as a verb, to wear away and spend unnecessarily or carelessly. Also to be wasteful is to expend what is valuable needlessly or uselessly. There is much in each of these definitions which does not appear to the casual observer; and in the average industry or household they can be broken down to a number of specific things. Also there are numerous reasons for them. For example, that which is unused may have been purchased without there being real need for it, it may have been purchased in excess of the required amount or quantity, it may have been replaced by something else and is therefore of no use for the purpose originally intended or its existence may be unknown. We cannot say that it is unproductive, worthless or refuse without analyzing it to determine whether there is any place where it can be used to advantage, either in its present condition or by economical modification. Therefore each article or kind of material presents its own problem.

Waste caused by wearing away may be the result of carelessness or negligence, for example, the rough usage or abuse to which many things are subjected. This is illustrated by the machine tool which is forced beyond its limit of endurance or the wearing parts of which are not lubricated as they should be. This same applies to the automobile, to the vacuum cleaner and countless other types of industrial and household equipment.

REFUSE is not so easily defined when we consider what chemistry has done and is doing to convert much of it into useful materials. There are many materials on the market today that are made of others which in the past were refuse, and keen competition has forced us to cull over the refuse pile and take out of it many things that were discarded under our former wasteful practices. Necessity is truly the mother of invention, and because of it, ways are being found to utilize much of that which was formerly thought to be useless.

To spend unnecessarily or carelessly is a very serious waste which applies both in industry and in the home. Industry requires an accounting for all expenditures, and in recent years those who spend unwisely are penalized for it; but the same is not generally true in the home when buying food stuffs, clothing, furnishings, etc. We must realize that everything offered for sale has in it an investment of labor and material, and if we do not use it wisely, it is an economic loss which cannot be recovered.

Industry has made much effort to lower the cost of its product by simplifying designs, paying bonuses for increased production and in many other ways. These, however, are not enough to meet the requirements, and it is necessary to look elsewhere for further savings. This can be accomplished by elimination of unnecessary waste and everyone can contribute something to it.

ONE of the principal wastes in industry is caused by rapidly changing designs, which are brought about chiefly by evolution or advancement of the arts Generally it is not possible to defer introduction of the new or superseding designs until all stocks of the old apparatus, parts and materials are used. This usually results in having to salvage considerable amounts of the superseded materials, because it is not ordinarily possible to use them to advantage elsewhere.

If designs were not changed and other more efficient or more economical apparatus and devices were not developed to replace existing materials, practically all of the waste we now have would be eliminated, except that which results from errors, abuse, deterioration and what might be called "mill ends". However, it is obvious that such a condition could not exist. From this it will be seen that waste is to some extent the price of progress, but it should not be assumed that it is always necessarily so.

The effect of obsolescence and changes is felt quite keenly in the industries which manufacture their products in great quantities, because there are always large amounts of parts and materials on hand. Large quantity production affords considerable savings in that the same machine tool and other set-ups can be used for long periods, and jigs, fixtures and other labor saving devices can be provided for the manufacturing operations; but it is very difficult, if not

*Revised from a lecture before The Westinghouse Club.

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impossible, to use all of this material when design changes are made.

Only that which is accepted as standard and is in general demand should be produced on a quantity basis. This class of product, however, forms the major part of the out-put of many manufacturing plants, and in order that the supply may be equivalent to the demand, which is quite irregular to say the least, it is necessary always to have large amounts of the finished product on hand. Also it is necessary to have large stocks of the constituent parts and materials in order that more of the finished product may be made quickly.

From the foregoing, it will be seen that quantity production and large stocks are vitally necessary in order to reduce manufacturing costs, and to have so-called standard products available for delivery immediately upon receipt of orders. The former should be given careful consideration when establishing the amounts to be manufactured on each set-up in order that there may be sufficient to obtain minimum costs and still not more than can be reasonably expected to sell. Also possible supersedure and obsolescence must be kept in mind, because these do occur, and at times when least expected.

Establishing the quantities to be carried in stock is not a simple matter if done with any degree of accuracy. Most manufacturers are guided largely by past activity. Such a guide is perhaps the best that can be had on many lines, but on others it is necessary to estimate the amount that the market will absorb, estimate the amount of that total business which each manufacturer should obtain, and generally size up the market as regards trend, competition, etc.

THERE are several things which must be watched closely if losses due to supersedures and other design changes are to be held to a minimum. The principal one is to have as much notice as possible of contemplated changes, in order that there may be ample time to use existing stocks before introducing the new or changed lines. Advance notice can generally be had, because the designer usually has the supersedure in mind for some time before actually putting it into effect. The exception to this is where sudden important discoveries are made and it is distinctly advantageous to put them into use immediately, even sacrificing a large investment in affected stocks. Such a condition, however, is not at all common.

The notice of contemplated supersedure should include a complete list of all finished apparatus, parts and materials that will be affected, and no more of them should be ordered except to match existing stocks and close out the line with as little as possible left over. In fact, it is best to cancel all stock authorizations immediately upon receiving notice of contemplated supersedure, and thereafter order specially such parts as are required to close out the line.

After the notice of contemplated supersedure is received, the next step is to ascertain the total amount of affected materials on hand and on order, and lay out a production schedule to dispose of them prior to introducing the superseding line. Stocks of renewal parts for the superseded designs should be provided and the amounts should be based upon the number of superseded units produced. However, our experience shows that in a factory it is uneconomical to stock more than two years supply, because interest on the investment, storage costs, etc., offset any advantage of manufacturing quantities when materials are held longer than that time.

No designs should be changed without first ascertaining the cost, and this is principally the loss on the stock investment, manufacturing equipment and tools of the old line. Furthermore, the changed designs should not be put into production until it has been determined what to do with all of these.

A VERY important thing in preventing large losses on supersedures and obsolescence is to keep all stock quantities as small as possible. Much has been done along this line in recent years, and where it was formerly customary to carry stocks sufficient for several months supply, it is now rare that we have more than 90 days stock, and in fact a great amount of business is being done on 30 days stock. When we learn how, we will probably carry not more than 30 days stock of the major portion of our materials—such as steel, copper and insulating materials—and will have them flowing in as needed.

When closing out changed or superseded products, the manufacturing equipment, jigs, fixtures and other tools should always be taken care of, otherwise they are apt to be forgotten. Inactive tools are a serious handicap, in that they have to be stored and recorded the same as active tools, they occupy valuable storage space, and tend to give an appearance of stagnation. Larger tool equipment generally has to be held on the manufacturing floors and when such equipment is unused, the situation is quite aggravated. Possible requirement of the tools for manufacturing renewals parts must be given consideration and if it is expected that there will be a renewals demand, they should of course be kept. However, where the demand is expected to be relatively small, and the parts can be made without the use of the original tools, it is quite often best to get rid of them at once.

The finished product of superseded design can generally be disposed of to much better advantage than can the parts and materials stocks from which it is made. Unless the change is extremely radical, and the superseding product considerably more efficient or more economical, the superseded product can generally be sold. This requires special sales effort, however, and one must have a thorough knowledge of the difference between the new and old products in order to present them intelligently to the trade. Occasionally it is necessary that the old product be reduced in

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price, because of its inferiority by comparison with the new. Occasionally the old product can be economically modified to the new design. All of this should, of course, be considered when the supersedure is first thought of, and definite plans should be made at that time.

DISMANTLING or tearing down apparatus and parts presents another problem which is at times difficult to solve. Some of the larger industries have found that they cannot afford to do dismantling work, because of their relatively high labor costs; and it has been found advisable to sell the material to professional wreckers, who can do the work in but a fraction of the time that would be required in the manufacturing plant. The reason for this can be readily seen when it is considered that the average industry simply reverses the building operations when doing dismantling work, and ordinarily uses the same tools; whereas the professional wreckers resort to the acetylene torch, explosives, skull crackers, etc., which enable them to do the work in much less time and at considerably less expense. Furthermore, the labor rates paid by professional wreckers are as a rule, lower than the rates paid in industry.

A great deal can be accomplished by watching the scrap pile and culling out the mill ends and discards. Analysis of the contents of the average scrap pile will suggest many things that might be done to advantage and several things will appear conspicuously. Some of these are as follows:—

Are the materials purchased in such lengths and sizes as permit their being used to the greatest advantage.

Does the manufacturing department do everything possible to obtain the maximum out of them?

Can the materials be used either "as is" or with economical modification on other products than those for which they were provided?

Can anyone else use the material to advantage, thus providing a better return than can be had from scrap?

Can the materials be treated in any way so as to make them useful?

An important thing in connection with waste prevention and reclamation work is welding. This applies both in the manufacturing processes and salvaging work. A large amount of pattern and casting work is being replaced by welding, also many structures formerly riveted, bolted or screwed together are now being joined by welding at considerable savings. The salvaging of steel castings by welding blow holes and other defects either inherent in the casting or caused by defective workmanship, is quite profitable, and advantage should always be taken of this development. Short ends of bar, rod and pipe stock can occasionally be welded advantageously.

There are certain characteristics which one should possess in order to look after waste prevention work intelligently. These are briefly as follows:—

*Instinct,* which may be classified as the impulse which leads the individual to detection of waste, whether in materials, processes or what-not.

*Imagination* has to be employed in order to discover better and more economical ways of doing business, and thus preventing the waste first detected.

*Resourcefulness* requires a knowledge of methods and processes ordinarily employed in industry as well as inventive genius, in order to determine whether the thing imagined can be made an economic reality.

*Balance or Sense of Proportion* is that by which one determines economic factors, and which enables one to distinguish between that which is worthwhile and that which is not.

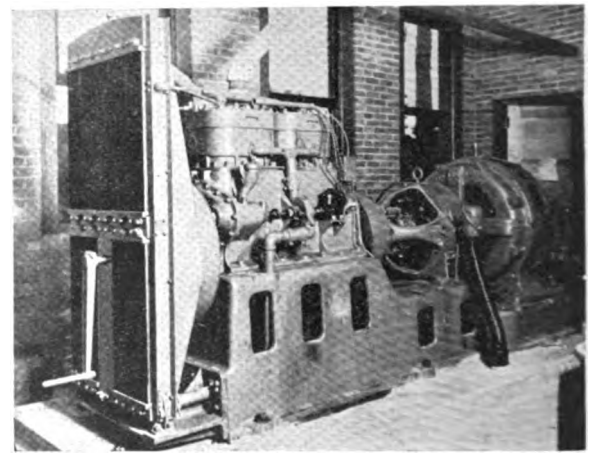
LITTLE has been said here about the home. It is obvious that the principles advocated for accomplishing waste prevention and the freeing of frozen assets in business should be at least equally successful in the home.

Above all else, the principal thing is to instill in everyone a feeling of responsibility as regards the materials and equipment with which they work, and in fact as regards everything with which they have anything to do. This same feeling of responsibility must be instilled in the minds of all who serve industry, to the end that they may be just as diligent as if they were doing it for their own immediate personal profit. When such an attitude is taken by all, the problems of waste and frozen assets will be well on the way to solution.

## An Emergency Power Unit

An absolutely reliable supply of current is a fundamental requisite for any railway automatic signaling system. In order to insure continuity of power supply it is customary in alternating-current signaling, to have available two separate source of power to feed each section of the signal line; one source for normal feed and the other for emergency feed.

The Pennsylvania Railroad in installing its automatic train stop and wayside signaling system on the Panhandle Division, between Pittsburgh and Newark, Ohio found it impracticable to purchase suitable power at Cadiz Junction. Therefore, to supply it, a remotely controlled power plant was installed. It



consists of a 100 b.h.p. gasoline engine, cranking motor, alternator and exciter all direct connected. Should the normal current fail the cranking motor will be automatically connected to a storage battery, crank the gasoline engine and in less than six seconds the alternator will be carrying the load. The alternator is rated at 50 kv-a at 100 cycles, 1000 r.p.m., one hundred cycles was chosen for the signaling system as that frequency eliminates the possibility of inductive interference from commercial circuits.

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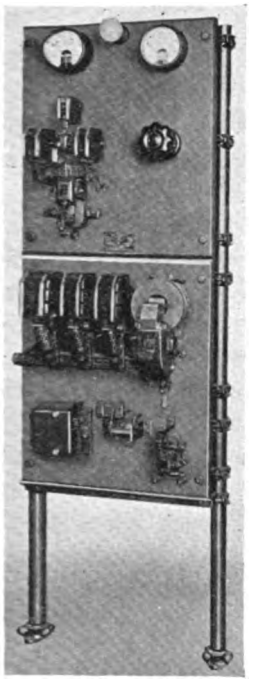
FIG. 1—A LOW VOLTAGE, LINE VOLTAGE STARTER



# Magnetic Control for Synchronous Motors

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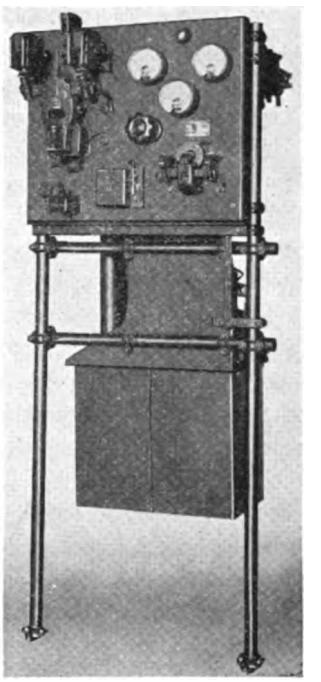
**The use of synchronous motors is growing rapidly. They are being applied wherever they can successfully meet the operating requirements, as they can be used to improve the power-factor as well as to drive their attached load. Due to the larger starting and pull-in torques obtainable with the newer designs, the number of suitable applications has been increased. As a result, we may reasonably expect the synchronous motor to enjoy an even greater popularity in the future.**

FIG. 2—HIGH VOLTAGE, LINE VOLTAGE STARTER



IT is usually safer and better to start synchronous motors by means of automatic or magnetic controllers. This removes the human element from the starting operation, prevents the field from being prematurely excited, prevents changeover to full voltage before the motor has accelerated sufficiently, and as a result, prevents unnecessarily heavy current peaks in the line, mechanical shock to the motor and attached machinery, and the possibility of the motor not being able to pull in, due to premature excitation. Of course, all of the desired results can be accomplished with a manual controller. The best of operators, however, are liable to err occasionally, resulting in poor starting conditions, while the inexperienced operator will often do this.

In addition to the better starting conditions secured by automatic control, the operator's hands and mind are freed for more important work. This enables him to concentrate on the driven machine and the job at hand. These considerations should produce dividends in the form of added production.

Automatic and magnetic controllers also permit the control panel to be placed in any available space that is reasonably near to the operator, the motor and the driven machine. It is only necessary that the pushbutton station or master switch be easily reached by the operator.

Synchronous motors are started either on full or reduced voltage depending upon the size of the motor, its speed, the torque requirements during starting, the ability of the motor to accelerate its load from standstill, the application, and the policy of the power company in regard to current peaks during the starting period. It is, of course, advisable to use full voltage starting whenever possible, as the control for full voltage is much simpler and cheaper.

### THE LINE-VOLTAGE STARTER

Any line-voltage synchronous motor controller should have a line switch for connecting the motor to the alternating-current supply, a field switch for connecting the motor field to the direct-current supply, an overload relay for protecting the motor from overload conditions, and a field rheostat for regulating the field current and the power-factor. To these necessities are usually added auxiliaries and accessories, such as low voltage and protective relays, indicating lights, starting and discharge resistors, line and field ammeters and often a power-factor meter. Other apparatus may be necessary if the control scheme is of a more complicated nature.

A control panel such as indicated above, except that the power-factor meter is omitted, is shown in Fig. 1. This shows a small panel carrying a reasonably small amount of apparatus. This is a very desirable characteristic of line-voltage starters, as it results in:

1—Lower first cost.
2—Fewer parts to get out of order.
3—Lower upkeep.
4—Greater simplicity.
5—A better understanding of apparatus.
6—An appreciable saving in floor space.

The three-pole magnetic contactor, when magnetized, connects the motor to the alternating-current supply and upon being demagnetized, opens all three phases (in a three-phase line), removing the motor from the line. This starts and stops the motor. The contactor shown is a common, magnet-operated, air-break switch having each pair of contacts equipped with a blowout coil and an arc chute for quickly break-

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ing the arc when the circuit is opened. For voltages above 600, oil-immersed line switches such as shown in Fig. 2 must be used. An inspection of Figs. 1 and 2 shows that a change in line switches does not change the other apparatus used. The oil switch is in effect a small magnet-operated circuit breaker.

The field contactor is of the field frequency type, that is, it automatically applies the field when the motor reaches approximately 95 per cent of synchronous speed. Two pairs of make contacts are provided for placing the field across the direct-current supply and, as fairly large currents must be broken, blowouts are provided for these contacts. The normally-closed lower contacts connect the starting and discharge resistor across the motor field during the starting and discharge periods, but open the resistor circuit when the upper contacts close to energize the field. These lower contacts are held tightly closed, and the contactor kept in the starting position during the starting period, by the lower magnet and coil which is energized by the induced current generated in the field windings during starting.

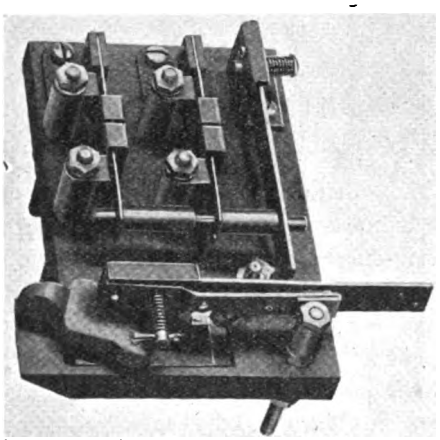

FIG. 3—A THERMAL OVERLOAD RELAY

An interlock with a blowout is mounted between and above the two main poles of the contactor. This interlock has its contacts in parallel with the bottom contacts of the contactor. It is operated by a lever attached to the moving armature, is normally closed, and is so adjusted that it does not open its contacts until after the main contacts close. It recloses its contacts before the main contacts open. In other words the interlock contacts and the contactors upper contacts over-lap, so that the field circuit is never open. This prevents the high discharge voltages which otherwise would be built up when the contactor suddenly opens the field circuit.

The overload relays commonly used are of the thermal type which are the best yet developed for the protection of motors. As their heating follows rather closely the heating of the motor, they permit short or intermittent overloads which do not harm the motor; and remove the motor from the line if the overload continues until the motor temperature approaches the danger point. The motor is thus amply protected, and at the same time is removed from service only when it is absolutely necessary. Due to its inherent time delay, this relay will not open the circuit under short-circuit conditions until the circuit breakers farther back in the line have had ample time to remove the short-circuit from the line. This prevents the excessive burning that would damage the line contactor should it open under these severe conditions.

The thermal relay may be either the hot-wire expansion type, the solder-pot type or the bimetal strip type. The bimetal strip, shown in Fig. 3, is most favored and is probably the best thermal relay yet developed. It consists of two bimetal strips which are straddled by two heaters placed in the secondary circuits of two current transformers in two of the incoming lines. The heat produced thus depends upon the current flowing in the line. The bimetal strip is made by welding together two metals which have widely different coefficients of expansion. As a result, as the strip is heated one metal expands more than the other, causing the strip to bend or curl. The relay shown is arranged to have the curling strips operate a pushrod which, after a certain predetermined travel, which is adjustable, trips a latch, quickly opening the control circuit, and disconnecting the motor from the line.

A rheostat for the exciter field or for the motor field may be used, depending upon the source of direct-current for exciting the field. If the direct-current is generated by an individual exciter or motor-generator set, an exciter field rheostat is cheaper and dissipates less power in the resistors. This type of rheostat is usually mounted on the rear of the panel and is operated directly by the rheostat handle shown on the front of the panel. A motor field rheostat, because of its size, must usually be mounted above the panel, on the floor, or in some nearby place. It is operated by the same rheostat handle through a sprocket chain. A combination mounting may be used which will permit the use of both types of rheostats if desired.

An elementary diagram for the panel in Fig. 1 is shown in Fig. 4. To start the motor it is simply necessary to press the pushbutton. This energizes the low-voltage relay, which closes and energizes the coil of the line contactors 5. At the same time, the low-voltage relay closes its interlock which, by short-circuiting the start button, provides a holding circuit for itself. The closing of the line contactors, 5, places the motor on the line, and at the same time energizes 32, the upper coil of the field contactor through an interlock. The field contactor would now pick up were it not locked out by 32A, the lower magnet and coil, which is also energized. When the motor is placed on the line, the current flowing in the armature windings of the motor, through transformer action, induces a current in the field which energizes 32A, the lower magnet. Thus, the top and bottom magnets are excited at the same time.

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The motor now starts as a squirrel-cage motor due to the torque derived from its squirrel cage, and its field windings. A starting resistor is usually placed in the field circuit during starting as this materially increases the starting torque of a synchronous motor. The acceleration will normally continue until the motor has reached from 95 to 97 percent of synchronous speed, from which point it may be pulled into step when the field is excited.

With alternating-current applied to the stator, the induced field current at standstill will have a frequency equal to line frequency. As the motor accelerates, this frequency will decrease, remaining proportional to the slip of the rotor. As the impedance is almost proportional to the frequency, and as the induced current equals the induced voltage divided by the impedance, the current induced in the closed field circuit during starting remains approximately constant from start until the motor nears synchronous speed when it drops somewhat, as the impedance at a low frequency is influenced less by the reactance and more by the resistance of the circuit. At this very low frequency, the greatly increased time required for the induced alternating current to reverse and pass through zero gives a comparatively long period of low torque in the lower magnet. This torque, being lessened further by the decreased induced current flowing, falls to such a value that the upper magnet overcomes the lower magnet at about 95 to 97 percent of synchronous speed and allows the motor field to be connected to the direct-current source. As the lower contacts are opened the circuit through 32A is opened and the lower magnet no longer exerts any pull. The field is now energized, the motor pulls into step and is ready to carry its load.

As soon as field contactor 32 closes, a protective relay 33 operates to remove the short-circuit around the resistor in series with the coil of contactor 32. This prevents over heating of the coil and permits the direct-current switches to operate satisfactorily over a wide range of voltages. The coil of the protective relay has a very wide range of voltages and the use of the resistor gives the field contactor a similar range, at the same time giving a positive pickup.

The indicating lamp shown at the top of the panel in Fig. 1 glows while the field is excited, thus showing the operator that the motor should be in step and ready to carry its full load.

The direct-current ammeter is placed in the motor field circuit and, after the field is excited, shows the amount of direct-current flowing through the field. During the starting period, and before the field contactor is closed, the induced alternating current flows through the ammeter. This causes the needle to vibrate with the current alternations. The decreasing frequency of the vibrations indicates the approach of the motor to synchronous speed. After the field is excited, the field current may be adjusted to the proper value by means of the field rheostat.

With a motor designed to operate at unity power-factor, the direct-current excitation may be adjusted to give unity power-factor by changing the field current until the line current is reduced to a minimum. If a power-factor meter is a part of the equipment this adjustment is, of course, more easily made.

To stop the motor the control circuit is broken by depressing the stop pushbutton. The overload relay does the same thing under overload conditions. In either case the low-voltage relay drops out, followed by the line and field contactors. Their action is easily traced from Fig. 4.

Under low voltage conditions, the low voltage relay and the line contactor drop out, followed immediately by the field contactor. The holding circuit is broken and the controller will not again start until the pushbutton is depressed by the operator. In case of

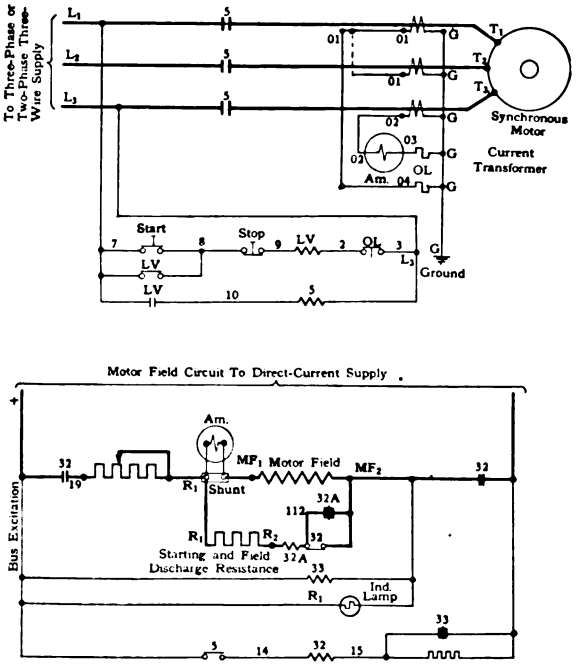


FIG. 4—A SIMPLIFIED DIAGRAM OF THE LOW VOLTAGE, LINE VOLTAGE STARTER

single-phase operation, pullout or loss of excitation the line current will be greatly increased and the thermal overload relay will operate to remove the motor from the line.

Pressure gauges, float switches, walking beam pushbuttons or other types of master switches may be used for controlling a panel of this kind simply by substituting for the spring return pushbutton shown.

Some typical applications for the starter just described are: blowers, air compressors, ammonia compressors, rubber and cement mills, mining machinery, motor-generator sets and centrifugal pumps.

### REDUCED VOLTAGE STARTING

It is usually recommended that low speed and medium speed synchronous motors be started on full line voltage; whereas, in order to keep the required starting current relatively low, high speed synchronous motors are often started on reduced voltage.

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Starters of the reduced voltage type therefore, have their application under conditions of limited feeder capacity and minimum line disturbance.

Although reactors and resistors are sometimes used for reducing the voltage applied to a motor during starting, the customary way is to use an autotransformer. Therefore, only the autotransformer method will be considered.

In addition to the material required by the line voltage starter, the reduced voltage starter requires a starting contactor or contacts for connecting the autotransformer to the line and to the motor during the period when reduced voltage is required, and a means for transferring from reduced to full voltage at the proper time. The other apparatus is identical or similar.

*Magnetically Operated Auto-Starter*—One type of reduced voltage starter recently developed uses the

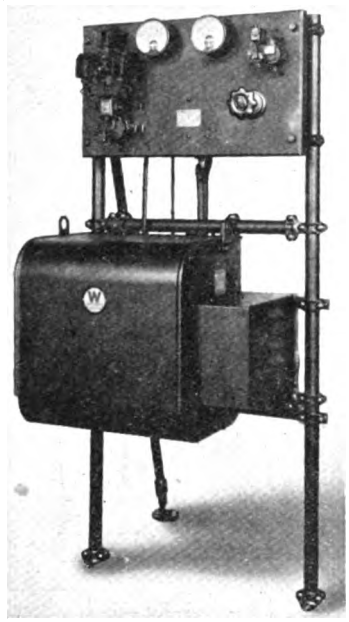


FIG. 5—A MAGNETICALLY OPERATED, AUTOTRANSFORMER STARTER

magnetically operated auto-starter for controlling the lower voltage alternating-current circuits where the rating does not exceed 100 hp. This auto-starter contains an overload relay, starting and running contacts, a timing relay and provides a method for changeover from reduced to full voltage. The field contactor, field rheostat, protective relay, meters and starting discharge resistor are provided as in the line voltage starter previously described. Such a starter is shown in Fig. 5.

The auto-starter, an inside view of which is shown in Fig. 6, is one of the magnetically operated starters commonly used for starting squirrel-cage motors. It has two sets of contacts attached to one shaft, with five pairs of starting contacts on one side of the shaft and three pairs of running contacts on the other side of the shaft. To start the motor on reduced voltage the starting contacts are closed. When transferring to full voltage, these starting contacts are opened and the run contacts closed. In the manually operated auto-starter a handle is provided by means of which the operator makes the desired connections. The magnetically operated starter substitutes for this handle, two magnets with coils and one common moving armature. The starting magnet is first energized and as the armature is attracted, the starting contacts are closed,

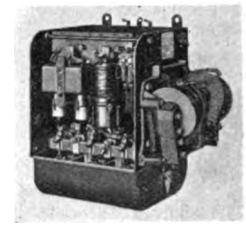
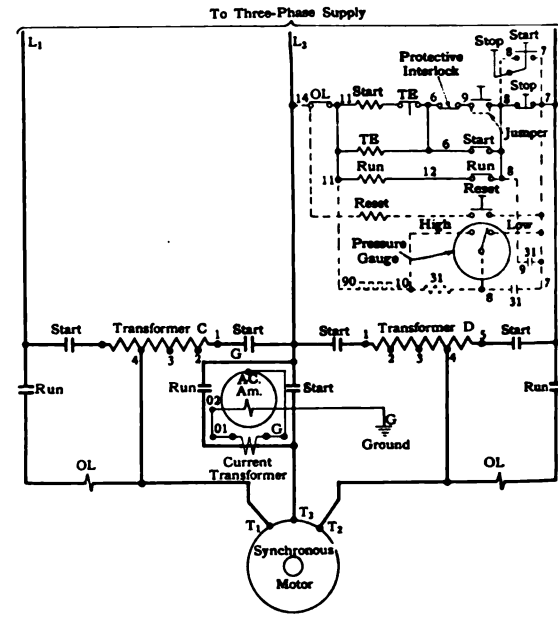


FIG. 6—AN INTERIOR VIEW OF THE AUTOTRANSFORMER OF FIG. 5

placing reduced voltage on the motor. After a certain predetermined time, the starting magnet is deënergized, the armature is released, the starting contacts open and the armature and contacts swing to the run position with the run magnet energized. Full voltage is thus placed on the motor.

For accomplishing the change from reduced to full voltage, an oil dashpot accelerating relay actuated by a shunt coil is used. When energized, it trys to pick



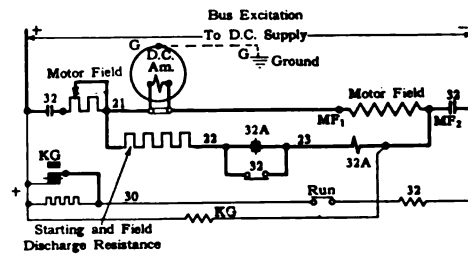




FIG. 7—SCHEMATIC DIAGRAM OF AUTOMATIC, LOW VOLTAGE STARTING ARRANGEMENT

up its plunger but this action is retarded by the action of the oil dashpot, which may be set to give any desired time within a considerable range. When this relay completes its travel, it opens its contacts, deënergizing the starting magnet, and energizing the running magnet. Transfer to full voltage immediately occurs

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The starter may be operated by a pushbutton, or any other type of master switch used by the operator. After pressing the pushbutton, the starting is fully automatic for the rest of the starting cycle.

This type of controller is a simple, cheap, compact piece of apparatus which provides reduced voltage

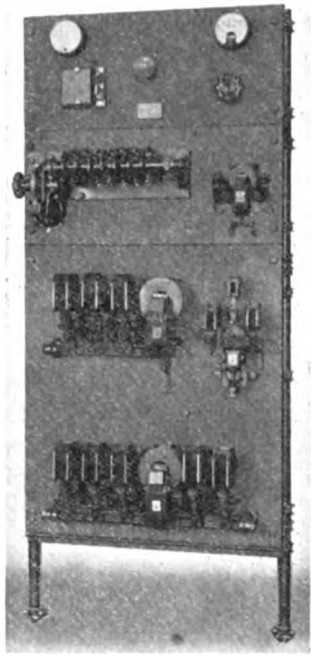

FIG. 8—A MAGNETIC, REDUCED VOLTAGE STARTER FOR LOW VOLTAGE MOTORS

starting of the smaller motors operating at voltages up to 600. It may be readily adapted to any type of remote or automatic control.

*Panel Mounted Contactors*—For the larger motors and motors using higher voltages, control panels similar to those seen in Fig. 8 and Fig. 9 are commonly used. Such panels use magnetic contactors for making the starting and running connections, and may be used for starting motors ranging in capacity from 25 to 1250 horse-power and in voltage from 220 to 6600 volts. They are compact, attractive and simple as they use comparatively few pieces of apparatus. As a result of these features, the apparatus is comparatively cheap and is becoming very popular with industrial concerns using synchronous motors.

In addition to the apparatus used on the line voltage starter previously described, the controller shown in Fig. 8 uses a five-pole starting contactor and a motor operated timing and transfer drum, which provides definite time operation of contactors and fixes the sequence of starting. The running contactors, meters, lamp, rheostat, overload relay and resistors are identical with those used with the line voltage starter. However, the low-voltage relay has two poles instead of one, and the protective relay is omitted, as one of the contacts operated by the timing drum takes its place. The field contactor also is operated by the timing drum on a definite time basis, rather than employing the field frequency principle.

An overload relay of the magnetic, inverse time limit type is used to protect the motor against overload. It effectively protects the motor, yet provides a time element permitting the motor to carry the slight overloads that would not harm the apparatus. This overload relay is mounted inside the cover and is an integral part of the auto-starter. It is normally provided with electric reset so that after an overload has removed the motor from the line, the operator may reset the relay from his pushbutton station, thus preparing for another start without being forced to open the cover and reset the relay by hand.

The STARTING contactor shown on the bottom of the panel in Fig. 8 is a five pole contactor similar to the RUN contactor except that it carries the five contacts necessary for properly connecting the autotransformer between the motor and the line. In a larger low-voltage type one 3-pole contactor and one 2-pole contactor are substituted for the 5-pole contactor, while for high voltage applications where oil switches are required, two 3-pole oil switches are used to make the starting connections.

The motor operated timing drum is a small, cam controller rotated or driven through a set of gears by a small single-phase induction motor. The cams are of duck micarta and may be cut to open and close their contacts at any point as desired. Thus any timing can

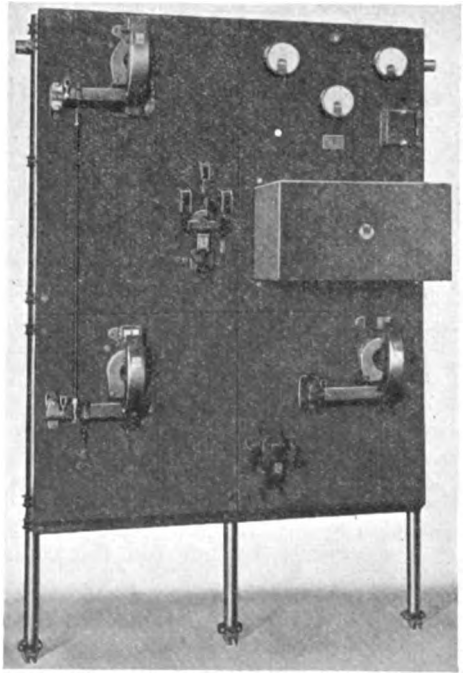

FIG. 9—A MAGNETIC, REDUCED VOLTAGE STARTER FOR HIGH VOLTAGE MOTORS

be secured, for changeover from reduced to full voltage, for applying the field and for controlling the pilot motor itself. With the cams cut as for these controllers, six positions for starting and running are secured and one additional for the off position with all switches open. This timing drum has been found to operate with entire satisfaction, and makes this control

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very desirable for reduced voltage synchronous motor starting. The timing can be changed to meet special conditions which might require a longer or shorter starting cycle.

The field contactor is the same contactor used on the other types of controllers, previously described. A shunt coil is substituted for the series coil used with the field frequency scheme of operation. This lower shunt coil and magnet still acts to lock out or lock open the upper or field contacts during the accelerating period until the proper time for applying the field. The circuits for both the upper and lower coils of this contactor are controlled by the timing drum. The

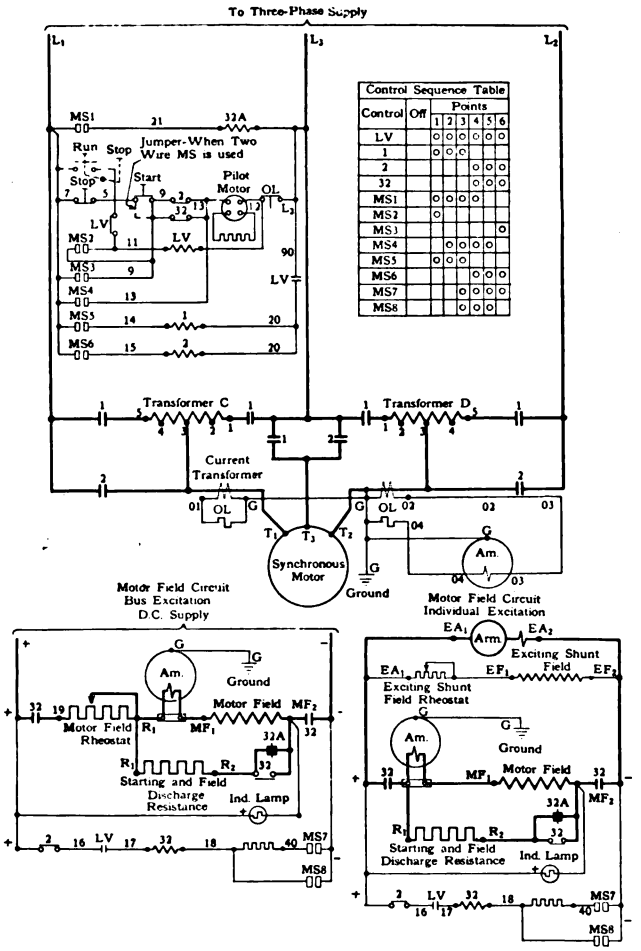


FIG. 10—A SIMPLIFIED DIAGRAM FOR REDUCED VOLTAGE MAGNETIC STARTERS

lower coil is energized, locking out the contactor, before alternating current is applied to the motor, and is not deënergized until the field is to be excited. The upper coil is energized shortly before the field is to be energized but cannot pull up its armature until the lower coil is deënergized, at which time it pulls in, closing the field circuit.

An elementary diagram of the panel of Fig. 8 is shown in Fig. 10. Pressing the start button energizes the pilot motor, which starts rotating the timing drum. As the drum rotates, it closes circuits to the lower coil of the field contactor, the low voltage relay, and to the start contactor, which connects the motor to the reduced voltage taps of the autotransformer, which is itself connected to the line by this contactor.

After a definite time interval, the drum operates to open the start contactor, and close the run contactor, placing line voltage on the motor. After another time interval the upper coil of the field contactor is energized, followed shortly afterward by the deënergizing of the lower coil. The field contactor now closes, exciting the field, and the synchronous motor pulls into step.

The timing drum now closes its contact marked *MS*3 and opens its contact *MS*4, through which power for driving the pilot motor has been supplied. As this contact opens, the pilot motor stops and the drum is in the running position. Although *MS*3 is closed, the pilot motor will not run, as the interlocks in series with it, operated by 2, the run contactor, and 32, the field contactor, are both open, breaking the control circuit. In case either the run contactor or the field contactor should drop out, the pilot motor circuit would be completed and the pilot motor would rotate the drum to the off position, where it would stop with all switches open, after having removed all apparatus from the line. The control is now ready for another start.

When, due to high current in the line, the overload relay trips, opening the control circuit, the low voltage relay opens, removing all apparatus from the line, and stopping the motor. The motor cannot again start until the overload relay has been reset, which permits the timing drum to be turned to the off position. The operator can then start the motor by depressing the start button.

In case of low voltage, the low-voltage relay and the other alternating-current contactors will open, removing the motor from the line. The field contactor also opens, as its coil circuit is broken as the low voltage relay opens. With a resumption of normal voltage conditions the apparatus will not again pick up. Instead the pilot motor will rotate the drum to the off position in preparation for another start.

A pressure gauge, float switch or any other type of automatic or manual master switch may be substituted for the spring return pushbutton station.

## CONCLUSION

Magnetic starters for synchronous motors are largely supplanting the manual starters, as they are easier to operate, relieve the operator of much responsibility, provide better, more uniform starting for the motor and to a certain degree utilize waste space. Full-voltage starters are preferred where applicable, as they are cheaper, simpler and more compact. They have fewer parts and require little upkeep. Reduced voltage starters are sometimes necessary, however, to reduce the current peaks in the line. Both types of starters are developed to a high degree, and are dependable, inexpensive and compact. Magnetic starters can be secured that will satisfactorily handle practically any application.

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# Automatic Vacuum Gauges

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THE development of the steel tank rectifiers has created a demand for several types of automatic vacuum gauges. The purpose of such gauges is to turn on the vacuum pumps when the pressure reaches a certain definite value, prevent the power from being connected to the tank when the vacuum is too high, and cut the rectifier tank off of the line in case the pressure in the tank should rise to a dangerous value.

Gauges which are used for the starting and stopping of the oil pumps must usually operate between the limits of 1 and 20 millimeters. Those used for determining the vacuum in the rectifier tank operate between the limits of 0.010 and 0.040 mm.

The first type of gauge, shown in Fig. 1, is of very simple construction. The bulb *A* is connected to the vacuum to be controlled while the tube *B* is closed and is usually evacuated. By making the two arms of the U of unequal diameter the change of mercury levels in the smaller tube can be made practically equal to the gas pressure in *A*, and hence the gauge can be made to operate at a much lower pressure than a gauge with equal diameter arms. Suppose that the U had arms which were of the same diameter and that the pressure in the bulb *A* was one millimeter, then the difference in levels of mercury in the two arms would be 1 mm., but the change in levels in both arms from a good vacuum would be only 0.5 mm. As this separation distance is too short, such a gauge would not operate reliably at 1 mm. pressure, due to mercury sticking to the contact.

Suppose that *a* and *b* are the diameters of the bulb *A* and the tube *B*. Further assume that the mercury in *A* is depressed a distance *h* and the mercury in the tube *B* rises a distance *H*. Since the volume of mercury leaving *A* must be the same as that entering *B* we have

$$1/4\,\pi\,a^2\,h = 1/4\,\pi\,b^2\,H \text{ or } \frac{a^2}{b^2} = \frac{H}{h}$$

Suppose that the gauge has the following dimensions: $a = 1\frac{3}{8}$ in. $b = \frac{3}{8}$ in. Then $H = 13.44h$. Hence when $h = 0.074$ mm., $H = 1.00$ mm., which corresponds to a gas pressure in the bulb *A* of 1.074 mm.

In the construction of this gauge it is important that the tube *B* should not have too small a diameter. Otherwise the mercury sticks on the walls and the opening of the circuit does not occur at the same pressure every time. The glass and metal parts of the gauge should be baked out well at a temperature of about 500 degrees C. and then the mercury should be distilled into the gauge under vacuum. In this way all gases such as air, water vapor, etc. are removed and the likelihood of having the contacts eroded and the mercury dirtied is much diminished.

For the measurement and control of pressures existing in a rectifier tank, one of the following types of gauges must be considered.

1—Hot-wire gauge
  *a*—Resistance variation
  *b*—Temperature variation
2—Ionization gauge
3—Static viscosity gauge
4—Glow discharge gauge

In considering the suitability of the above gauges simplicity in construction, reliability of operation, insensitivity to changes in room temperature, and the possibility of their use in full automatic substations should all be borne in mind. Also, the material which goes to make up such a gauge must not be attacked by mercury vapor.

## HOT-WIRE GAUGES

If a filament is mounted in a glass bulb containing a gas whose pressure can be varied, the energy put into the filament must equal that lost by radiation and

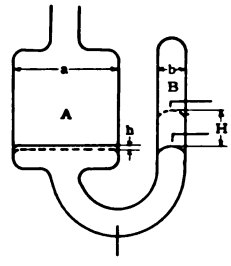


FIG. I—THE U TUBE VACUUM GAUGE

that carried away by the gas. From kinetic theory it is known that the heat conductivity of a gas is practically independent of the pressure. However, when the pressure is reduced to such a value that the mean free path of the molecules is large compared to the distance of the filament from the walls of the vessel, the heat conductivity of the gas decreases with decreasing pressure and hence provides a means of measuring that pressure. The temperature of the filament is kept low, usually around 100 to 150 degrees C., so that the losses due to radiation are small compared to the losses by conduction through the gas.

A hot-wire gauge such as the above may be used in several ways to measure the pressure.

*A*—A thermo-element may be mounted on the wire itself and used to measure the temperature changes with constant input to the heater.

*B*—The voltage across the wire may be maintained constant, and the change in current observed as a function of the pressure.

*C*—The resistance and hence the temperature of the wire, may be maintained constant, and the energy input required is observed as a function of the pressure.

*D*—The current through the lamp may be maintained con-

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stant and the change in resistance observed as a function of the pressure.

There are other ways of using a hot wire but they are too sensitive and cannot be used for automatic operation due to the adjustments which must be made.

*A*—The circuit arrangement for the thermocouple type of gauge is shown in Fig. 2. *A* is a constant voltage transformer, *B* is the filament wire and *C* is a nickel-advance thermocouple welded to *B*. *D* is a sensitive millivoltmeter provided with stops and electrical contacts, so that operation of the protective mechanism can be obtained at any desired pressure. The calibration for the standard 500 milli-ampere thermocouple bulb is shown in Fig. 3. It will be noted that this gauge is not very sensitive with respect to pressure changes. However, the sensitivity can be improved by using a filament B which has a large surface area, e.g. a flat ribbon instead of round wire. In using this gauge it is essential to maintain the voltage constant otherwise the change in temperature due to changes in voltage will be larger than those due to pressure.

Several ways of producing constant voltage are:—

*a*—Saturated core transformers.
*b*—Ballast lamps and transformer.
*c*—Glow tube regulator.
*d*—Saturated and unsaturated transformers with promaries in series and secondary fluxes bucking through one secondary winding.

Suppose the saturated transformer induces 120 volts in the secondary while the unsaturated transformer induces 10 volts 180 degrees out of phase with it. The resulting 110 volts will remain constant within 0.1 volt as the primary voltage varies from 100 to 120 volts. The temperature of the containing vessel must be constant otherwise the calibration of the gauge is changed.

*B*—This method is open to the same objections as those mentioned for the above gauge.

*C* and *D*—These two methods will be considered together as both employ the Wheatstone bridge connection. There are several ways of connecting the

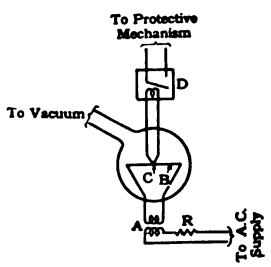


FIG. 2—SCHEMATIC ARRANGEMENT OF THE THERMOCOUPLE TYPE OF GAUGE

gauge but only one will be described here. A diagram of the circuit is shown in Fig. 4, which may be operated on either alternating or direct current. The gauges *A* and *B* are identical and are both placed in the vacuum to be measured. The filaments of *A* and *B* are made of nickel ribbon 0.015 by 0.001 in., four feet long and supported in the same manner as the filament in a tungsten lamp, except that the wire is welded to the supports. This is necessary in order that there be no changes in heat conductivity to the supports, and hence a change in resistance of the filament due to this cause. The wires should also be arranged so that they can not change their distance from the walls of the containing vessel and so cause a change in the heat conducted from the wire by the gas. The resist-

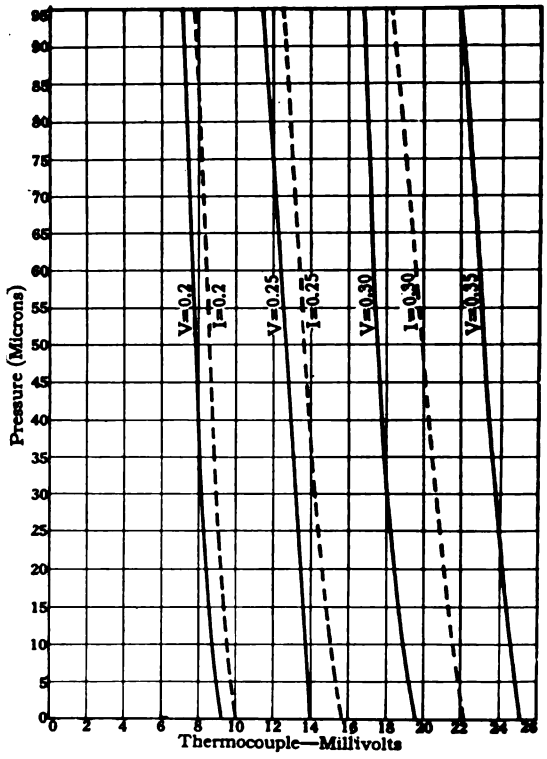


FIG. 3—CALIBRATION CURVES FOR THE THERMOCOUPLE GAUGE

ances $R_1$ and $R_2$ have a low temperature coefficient and may be mounted either in air or in the vacuum. The millivoltmeter may be provided with contacts which lead to the protective mechanism if so desired.

The calibration of this gauge, both with constant voltage across the bridge and also constant current to the bridge, is given in Fig. 5. Fig. 6 shows the variation of the millivoltage with changes in external temperature. Hence it can be seen that it is essential to

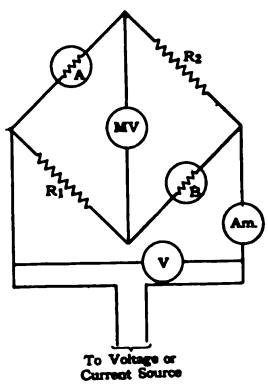


FIG. 4—ONE CIRCUIT DIAGRAM FOR THE BALLAST LAMP AND GLOW TUBE METHODS OF PRODUCING CONSTANT VOLTAGE

maintain a fairly constant temperature for the walls of the containing vessel. This difficulty can be overcome by interchanging *B* and $R_2$ and sealing *B* in a container having the vacuum at which it is desired to have the gauge operate. The container should also have some mercury in it. The arrangement compensates for

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any changes in room temperature but is not as sensitive as the device first described.

This device requires apparatus which will maintain the voltage or the current constant and since the

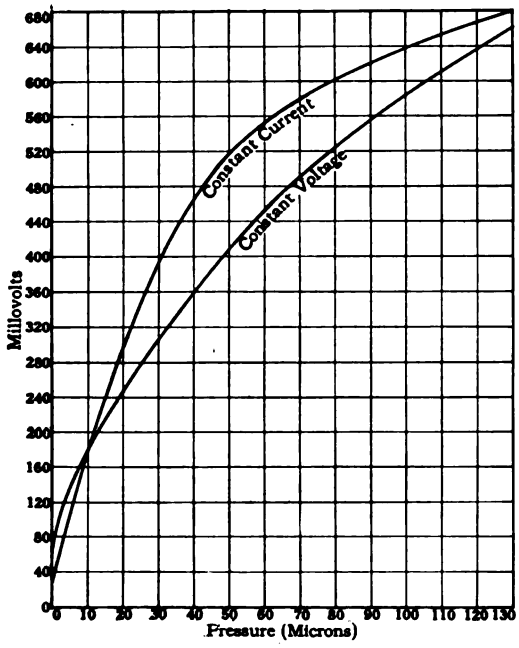


FIG. 5—CALIBRATION CURVES FOR THE CONSTANT VOLTAGE DEVICES OF FIG. 4

protective mechanism is operated by the pointer of the millivoltmeter, there is danger of the contact being poor or sticking.

## IONIZATION GAUGES

An ionization gauge can be very simply made from an ordinary three electrode tube such as the UV-200. However, in the construction of the tube it is essential that the supports for the various parts be made rigid, so that they can not change their spacing with respect to one another. The filament may consist of any sort of electron emitting source, such as

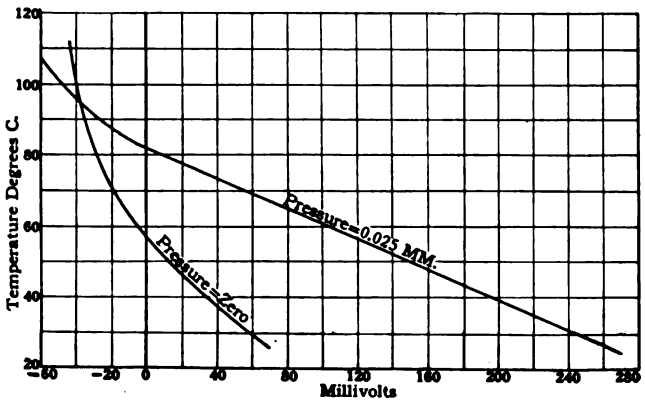


FIG. 6—VARIATION OF VOLTAGE WITH TEMPERATURE

tungsten. A positive potential is placed on the grid thereby drawing electrons to it. During the passage from the filament to the grid the electrons collide with the molecules of the gas and ionize them. If a negative potential is then placed on the plate of the tube, the positive ions are attracted to the plate and the current so measured can be made proportional to the pressure by properly adjusting the plate and grid voltages. Fig. 7 shows the calibration of such a gauge using air.

This type of gauge has several serious disadvantages when used as an automatic gauge. The electron current to the grid must be maintained constant; otherwise the ionization current to the plate will vary.

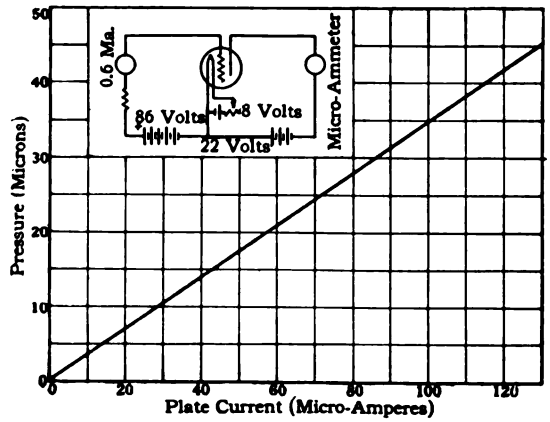


FIG. 7—CALIBRATION CURVE OF AN IONIZATION GAUGE

So far as is now known, there is no electron emitter which will have constant emission under varying conditions of gas and hours of life. Furthermore the filament temperature, and consequently its emission, changes with the pressure of the gas in the gauge.

## STATIC VISCOSITY GAUGE

A gauge of this type is constructed as shown in Fig. 8, in which $B$ is a metal disc which can be rotated at any desirable speed by means of the induction motor $CD$. The rotating disc tends to drag the air along with it and this in turn causes the disc $A$ to rotate. If $A$ is provided with electrical contacts and a spring $E$ to control the amount of the deflection, the contacts can be made to close at any desired pressure. The angle of torque on the upper plate by means of the rotating plate is given by the following equation:—

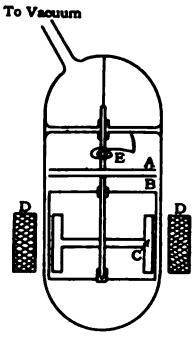


FIG. 8—ARRANGEMENT OF A STATIC VISCOSITY GAUGE

$$\alpha = \frac{\pi t^2}{8\pi k} A p \omega \sqrt{\frac{M}{RT}}$$

in which $t$ = natural period of oscillation of the disc $A$.
$k$ = moment of inertia of the disc $A$.
$r$ = radius of the disc.
$\omega$ = angular velocity of the rotating disc $B$.
$p$ = gas pressure.
$M$ = molecular weight of the gas.
$R$ = gas constant.
$T$ = temperature of the gas.
$A$ = constant for given gas and surface.

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It should be remembered that for this equation to hold, the distance between the plates $A$ and $B$ should be small compared to the mean free path of the molecules of the gas. It is seen from this equation that the torque is directly proportional to the speed of rotation of the disc $B$ and also to the gas pressure. It seems that this should make a convenient form of automatic manometer.

It is not necessary that the parts $A$ and $B$ shall be discs. They can be made in any shape such as cylindrical, conical etc. Furthermore the discs $A$ and $B$ may be slotted so as to form fan blades and the device can be then used over a wider range of pressures.

## GLOW DISCHARGE GAUGE

A gauge of this type is a new departure from the gauges which have been used up to the present time. It operates on the principle of the variation of breakdown voltage of a gas with pressure. By properly choosing the distance between the electrodes and their size and shape the gauge can be made to operate over a range of from 1 to 40 microns.

The construction of the gauge should be such that a high concentration of field can be obtained at one of the electrodes, that the field is fairly uniform and

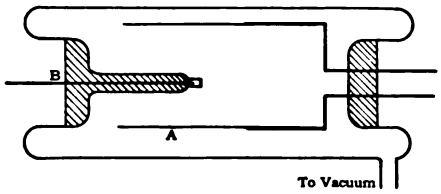


FIG. 9—ARRANGEMENT OF A GLOW DISCHARGE GAUGE

that the electrodes can be treated out readily. In order to meet these requirements a tube was constructed as shown in Fig. 9. The electrode $A$ is three inches long and one inch in diameter and should be made of material which will not react rapidly with the gases in the tube, and which will not sputter to any great extent. In this case aluminum was used.

In the case of the electrode $B$ it is necessary, for consistent operation, to confine the discharge to a definite portion of the electrode. This was done at first by placing a glass tube over the electrode; but it was found that during the operation of the tube, the discharge caused disintegration of the glass and consequent failure of the tube. In order to remedy this the electrode lead in wire was made of tungsten and the glass was melted to it over all its surface except the end of the rod, which was covered with a small cylindrical cap of treated graphite. The operation was found to be quite satisfactory, and Fig. 10 shows the calibration curve for this tube.

The circuit finally adopted for this type of tube is shown in Fig. 11. The high impedance, high voltage transformer $T$ is supplied by means of an auto-transformer so as to give adjustment of the voltage and thus the pressure at which it is desired to have the relay operate. In order to take care of irregular breakdowns which occur, a slow acting relay is used. The relay is placed in the low-voltage side of the

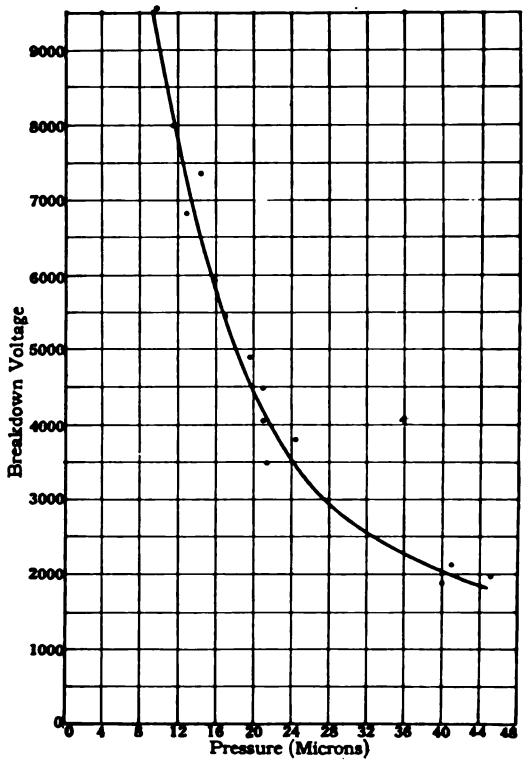


FIG. 10—CALIBRATION CURVE FOR A GLOW DISCHARGE GAUGE

transformer and is operated by the change in primary current, which may jump from 0.5 ampere at no load to 3.0 amperes when the glow tube is broken down. The mercury U tube is used to prevent the circuit breakers from being thrown in when the pressure rises to such a high value that the glow tube does not operate.

## CONCLUSIONS

The glow tube relay was thought to be the best and was developed. A modified form is now in operation as standard equipment.

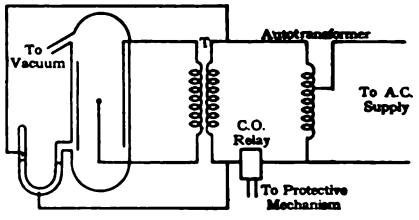


FIG. 11—A PRACTICAL CIRCUIT ARRANGEMENT FOR A GLOW DISCHARGE GAUGE

It would seem desirable to build and test a static viscosity gauge, should occasion arise for a relay which should operate at a lower pressure. It may be possible to make a vacuum fan type of relay which will operate at pressures from 0.05 millimeter up.

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# The Development of the Feeder Voltage Regulator

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THE rapid expansion of the alternating-current distributing system brought, with its many other problems, that of close voltage control. It was found that the life and candle-power of incandescent lamps were greatly affected by variations in voltage, necessitating some method of obtaining constant potential. To make the voltage drop negligible between generating station and the load would require a conductor size and spacing which would not be economical. Therefore some other means of controlling the feeder voltage at various loads is required.

At first it was sufficient to control the voltage of each generator by varying its field manually, as attempts at operating generators in parallel were, in

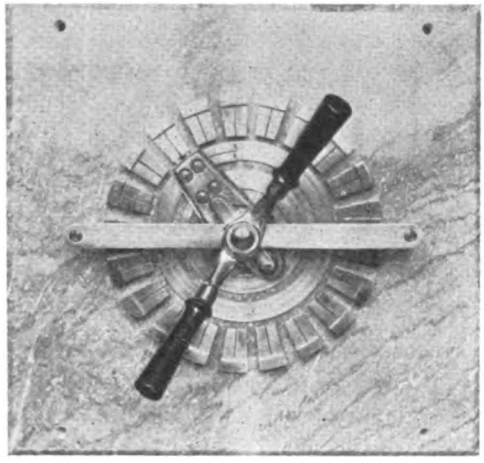

FIG. 1—THE DIAL OF THE STILLWELL, STEP-TYPE REGULATOR

general, unsuccessful. With improvements in the design of the generator and prime mover, generators were successfully paralleled and a number of feeders could be connected to a common bus. This practice required a new method of feeder voltage control. since the feeders might be of different capacity and length, and be loaded at different periods of the day. The voltage drop then would not be the same on each feeder.

The feeder-voltage regulator was developed, therefore, for the purpose of increasing or decreasing the outgoing feeder voltage so as to compensate for variable line drop or variable bus voltage, maintaining a constant voltage at the center of distribution or load center. The maintenance of constant voltage at the load insures proper operation of connected apparatus, and at the same time increases the revenue for the central station, thereby being of mutual benefit both to the central station operators and their customers.

Feeder-voltage regulators may be divided into two general classes; one in which the voltage is varied in steps is commonly known as the step type, and the other, in which the voltage can be changed gradually, or in an infinite number of steps, is termed the induction type.

The step or switch type of regulator consists of a two-winding transformer. The primary winding is connected across the line and the secondary winding is connected in series with the line and is divided into a number of sections which, by means of switching, can be put in or taken out of the circuit. The design of this type consists chiefly in the design of the switching equipment, since the transformers are simply modifications of standard apparatus.

The Stillwell regulator, invented in 1888 by Mr. L. B. Stillwell, was one of the earliest forms of the step-type of regulator. Fig. 1 is a photograph of the Stillwell dial. Two arms were used, one being connected through a brush to the inner ring and the other to the outer ring. A resistance was connected from one ring to the other so that the line circuit would not be opened while the potential was being changed by changing taps on the transformer.

A number of modifications of the Stillwell regulator have been made. Various schemes of connections have been devised, each designed to give the minimum disturbances to the line and apparatus during voltage adjustment. The step type can also be used in conjunction with an induction regulator, thus giving a gradual voltage adjustment. A number of large installations have been made using the step induction regulator and are giving satisfactory service. This combination is used for high-voltage, high-power

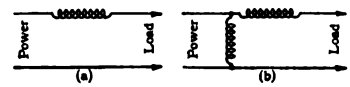


FIG. 2—SCHEMATIC REPRESENTATION OF SINGLE AND DOUBLE WINDING REGULATORS

installations, where the cost of an induction regulator of equal capacity would be prohibitive.

It is very difficult to control the step-type regulator automatically. The induction type has practically superseded the step-type of regulator since it can easily be adapted for automatic operation and does not have the objectionable switch contacts.

The induction type voltage regulator may be divided into two types; the single winding and the double winding. The single-winding type, which is one of the simplest forms of regulator, is connected in series with the line, as shown in Fig. 2 (a). The load current is the magnetizing or exciting current and

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the voltage induced is dependent upon the load current and the reluctance of the magnetic circuit. The double winding type consists of two windings, as indicated in Fig. 2 (b), one being connected across the line and the other in series with the line. The winding connected across the line is designated as the shunt or primary winding, and the series winding is called the series or secondary winding. A field which is practically independent of the load current in the series winding is produced by the exciting current in the shunt winding. Thus the two-winding type has the distinct advantage of producing a voltage in the series winding which is not only in phase with the line voltage, but is practically independent of the load. The principle of operation is to vary either the mutual induction or the ratio of turns.

One of the first pieces of apparatus to be used as a feeder-voltage regulator was an adjustable choke or reactance coil connected in series with the line. In its use the bus voltage was increased to a value such that, at full load, the bus voltage less the line drop would produce the required voltage at the load. The reactance coil was then adjusted at other loads so as to produce an artificial drop, and thus keep the potential drop between the bus and the load constant.

The kilovolt-ampere rating of the reactance coils was necessarily large in comparison to the kv-a of the feeder, since they had to be designed to give maximum voltage at light loads, and also carry the full load current continuously without a dangerous rise in temperature. The copper section is determined by

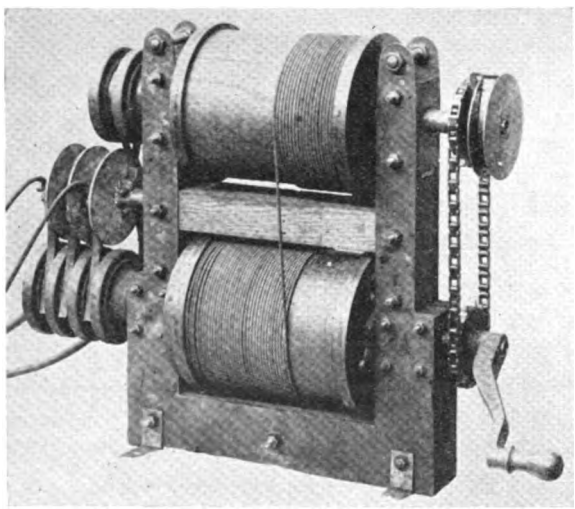

FIG. 3—THE WINDLASS TYPE DOUBLE-WINDING REGULATOR

the load current, and the number of turns by the cross-section of the core and by the maximum voltage required. Since the reactance voltage is in quadrature with the line voltage at unity power-factor, a high percentage of the line voltage is necessary to produce a small change in line voltage. To illustrate, in order to obtain a ten percent change in line voltage at unity power-factor, the required reactance voltage is approximately 46 percent of the line voltage. The apparatus is thus extremely large, as the copper section and number of turns are both large. Another very serious disadvantage of this type of regulator is that the voltage which is subtracted from the bus voltage is dependent upon the load.

A number of schemes were tried in adjusting the value of the reactance voltage. The first method that suggests itself is to vary the reluctance of the mag-

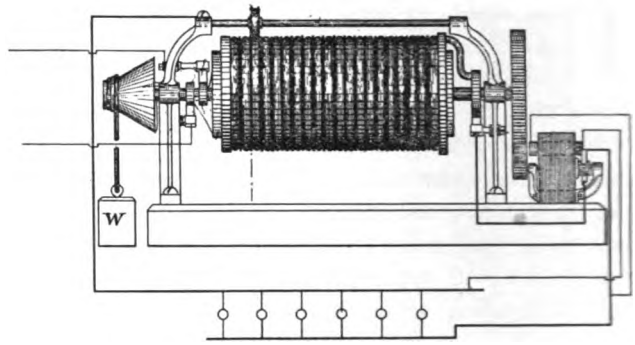


FIG. 4—THE SLIDING-CONTACT DOUBLE-WINDING REGULATOR

netic circuit by adjusting an air-gap in the circuit. This type of construction is very noisy. Another proposed method was to wind the reactance on a close magnetic core and then to saturate the core to a varying degree by using an auxiliary winding excited with direct current.

A transformer with one winding in series with the line and the other winding shunted with a variable resistance was used to a limited extent. The transformer would develop a high impedance with a high resistance across the secondary and a low impedance drop with the secondary short-circuited.

A synchronous motor combined with the reactance coil was designed to overcome the disadvantage of increasing the bus voltage and also to reduce the size of the reactance. The synchronous motor was connected between the reactor and the feeder. At light loads the field was adjusted to draw a lagging current, thus causing the reactance voltage to subtract from the bus voltage, and at heavy loads the field was adjusted to draw a leading current so that the reactance voltage would add to the bus voltage. This method involved the use of costly rotating apparatus, and was not widely used on short feeders. It is being used on long feeders at the present time, although the reactance is omitted, the natural impedance of the line being sufficient.

It soon became apparent that a transformer with a secondary inserted in the feeder circuit with a variable turn ratio would be highly desirable. Figs. 3 and 4 are two types which were designed with this in view. Fig. 3, usually referred to as the windlass type, consists of a primary or shunt coil mounted inside the lower drum. The magnetic circuit consists of transformer punchings which form the base and the core of the primary winding. The secondary winding is shown wound partly on the upper drum and partly on the lower. This winding is in series with the feeder

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and the voltage induced in it is dependent upon the number of turns enclosing the magnetic circuit; that is, it depends upon the number of turns wound on the lower drum. The ends of the windings are brought out through the center of the shaft to slip rings

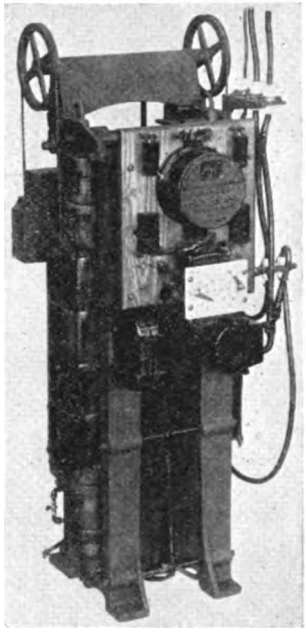

FIG. 5—A MOVABLE COIL TYPE, AUTOMATIC REGULATOR

mounted outside the magnetic circuit, to avoid placing a short-circuited turn on the magnetic circuit.

The sliding contact type shown in Fig. 4 accomplished the same results in a slightly different manner. The primary winding was located inside the secondary winding and mounted on an open iron core. The iron core consisted of a bundle of small, soft iron wires. The secondary consisted of a cable, suitably insulated between turns, and wound directly over the primary. The whole structure was rotated and the number of secondary turns in series with the line varied by the sliding contact which progressed along the secondary winding as the cylinder was rotated. The ends of the primary winding, and one end of the secondary winding, were connected to slip rings placed some distance from the ends of the core to avoid the effect of a short-circuited turn. An attempt was made to make this type automatic; i.e., to increase the voltage with increase in load to compensate for line drop. A torque motor was placed on one end of the drum and a weight $W$ was held by a cable passed over a conical drum at the other end. The torque produced by the motor was balanced by the weight $W$ operating on the cone; for increased motor torque the cone supplied an increase in lever arm increasing the resisting moment of the weight-cone combination until equilibrium was reached. Thus, when increased line current caused increased motor torque, the drum would be revolved through a certain angle dependent upon the weight $W$ and the shape of the cone. By suitable design, the change in drum position furnished a voltage increase in a definite proportion to the load current.

A radically different type of automatic regulator is shown in Fig. 5. It resembles the constant current transformers in appearance. In this type there are two primary coils $A$ and $A_1$. The coils are mounted on the center leg of the magnetic circuit and are so connected that their magnetic fields oppose each other, as shown in Fig. 6. The secondary winding $B$, which is connected in series with the line, is movable, its weight being counter-balanced by a weight. The regulator is shown in the mid or no-boost or buck position. If the winding $B$ is lowered a voltage will be induced in it which will add to or subtract from the feeder voltage, depending upon its polarity. If coil $B$ is moved upward, the induced voltage will be in the opposite direction. This means that the secondary voltage necessary will be only one half as great as that of an equivalent single-winding type. The value of the voltage induced in the secondary will depend upon how completely the secondary coils enclose the primary coils. A short-circuited coil was usually placed between the primary coils to reduce the impedance of the secondary in the mid or no-voltage position. The regulator shown is pneumatically operated, a piston and cylinder being located on the rear of the regulator. The automatic accessories are shown mounted on the panel with the current and potential transformers mounted directly underneath. This was probably the first successful full automatic regulator with compensation for line drop.

Another type of moving coil regulator is shown Fig. 7. There is only one primary coil A. The magnetic circuit is up through the primary coil and across the air-gap to the middle leg of the core and down. The air-gap is made large enough for the secondary coil to pass up to the upper part of the core. The secondary or series coil is movable and has the maxi-

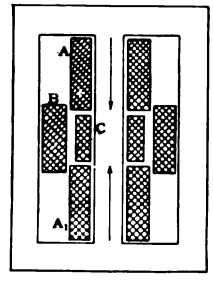


FIG. 6—THE COIL ARRANGEMENT OF THE REGULATOR OF FIG. 5

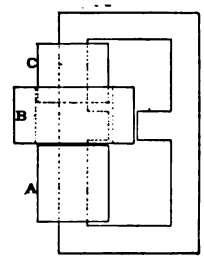


FIG. 7—A SINGLE PRIMARY MOVING COIL TYPE REGULATOR

mum voltage induced in it when it completely encloses the primary coil. The upper leg is provided with a short-circuited winding to reduce the impedance of the series coil when in the no-voltage or upper position. This type produces a voltage which adds to or subtracts from the line voltage, depending upon how it is connected. In order to obtain the full range of this type of regulator, an auxiliary switch is necessary so that the polarity of the secondary winding may be changed with respect to the line.

The induction type, which is the forerunner of

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the present-day induction regulator, is shown in Fig. 8. In this type the position of the main field with respect to the secondary winding is varied, instead of moving the secondary coil in relation to the field, as was done with the moving coil type. The stator is built up of annular punchings with four equally spaced slots. The

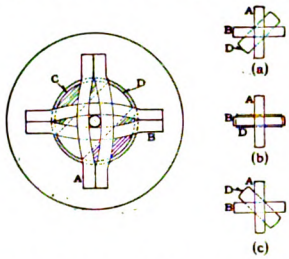


FIG. 8—AN EARLY, ROTATING COIL INDUCTION REGULATOR

primary coils *A* and secondary coils *B* are wound in the slots, the primary being 90 degrees from the secondary. The rotor is made up of essentially rectangular-shaped laminations. The main field, due to the exciting current, is practically constant, the magnetic circuit being through the rotor and around the annular laminations. The field which encloses the secondary

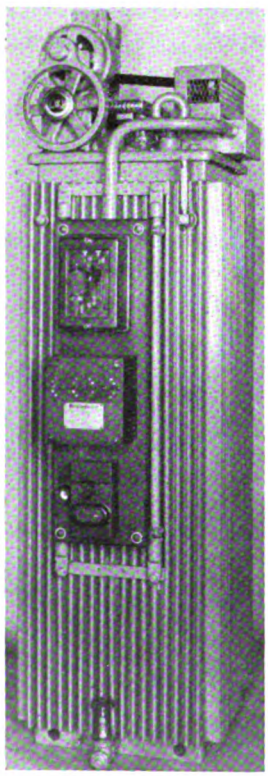

FIG. 9—A MODERN, SINGLE-PHASE AUTOMATIC REGULATOR

winding is variable, depending upon the position of the rotor. In the position shown in Fig. 8 (a), the flux encloses both coils *A* and *B* and the maximum voltage of a definite polarity with respect to the primary is induced in winding *B*. Fig. 8 (b) shows the mid-position, where the net flux which encloses winding *B* is zero, and therefore no voltage is induced in it. Fig. 8 (c) shows the rotor in a position which is similar to Fig. 8 (a), but the flux through coil *B* is in the opposite direction, so that the voltage induced is of opposite polarity to that of Fig. 8 (a). A copper shield is placed on either side of the rotor as indicated by *C*. This is used to reduce the effect of the stray field caused by the line current passing through the secondary winding.

The present type of single-phase automatic feeder regulator, commonly known as the induction type, is illustrated in Figs. 9 and 9 (a). The induction regulator is made up of two parts, a rotor and stator, as shown in Fig. 9 (a). The primary is usually wound on the rotor. The flux which threads the primary is

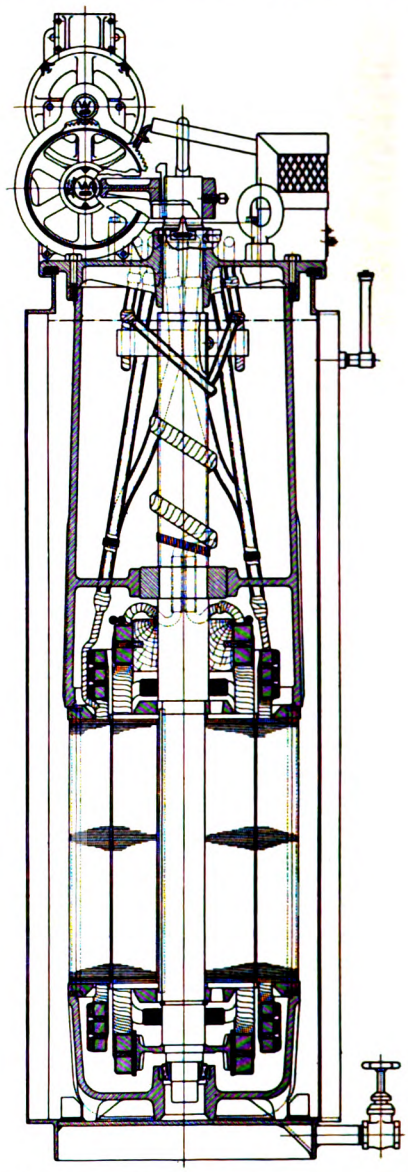

FIG. 9 (a)—THE REGULATOR OF FIG. 9 IN CROSS-SECTION

constant and its direction is always parallel to the diameter of the movable rotor which passes through the center of the primary windings. The direction of this flux with respect to the secondary can be varied by turning the rotor.

The rotor can be turned slowly, so as to vary the amount of flux enclosing the secondary windings, thereby obtaining a gradual change in voltage which adds to or subtracts from the primary voltage depending upon the relative direction of the main field.

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There are two windings located at right angles to each other on the rotor. The second winding is short-circuited upon itself in order to reduce the impedance drop in the secondary winding in other than the maximum position. Since the current in the secondary windings is dependent only on the load or the

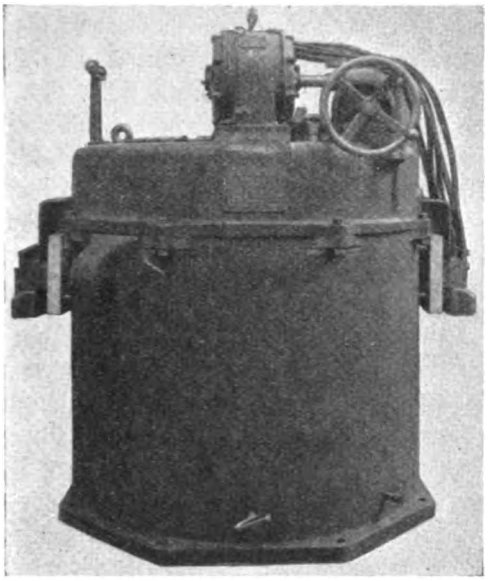

FIG. 10—AN EARLY THREE-PHASE REGULATOR

feeder current, this current would result in a high reactance drop in the secondary when in the neutral or mid-position. Assuming the exciting or magnetizing current to be approximately one-third the full-load current, it would require three times normal secondary voltage to force full-load current through the secondary, neglecting saturation of the core. The short-circuited winding reduces the voltage necessary to approximately ten percent normal voltage.

The three-phase regulator was originally introduced in connection with the rotary converter. The direct-current voltage was varied by controlling the alternating-current voltage. The three-phase induction regulator is essentially the same as a wound rotor induction motor with the phases separated and placed in series with the line. Figs. 10 and 10 (a) show one of the first three-phase air-cooled regulators for use with a rotary converter. The series winding is on the stator and consists of heavy copper straps, as the converters are low-voltage, high-current machines.

A modern air-cooled induction regulator is shown in Fig. 11. The proportions of this machine are vastly different from the earlier machines, due chiefly to the different application. In order to have the series winding carry the heavy converter current, the regulators were made with a large number of poles and the poles connected in parallel. This produced a comparatively short machine of large diameter. The booster-type converter has largely replaced the induction regulator type for this application, but the three-phase regulators are now used as feeder-voltage regulators. The feeder voltage is much higher than the converter voltage and the current is consequently lower for the same kv-a rating. This permits the use of a small number of poles in the design of modern three-phase regulators. The small number of poles produces a machine of relatively small diameter and which costs less to manufacture than the older type.

The series winding of a feeder regulator is connected so that it receives all the surges and disturbances peculiar to transmission lines. The windings are heavily insulated and braced for these conditions and experience has shown that this problem has been solved in a very satisfactory manner*. In order to reduce the ground insulation to a minimum, the slots are made large and few in number. Care must be taken in the design of the slot and tooth widths so that there will be no magnetic tooth locking.

The induction regulator is inherently a noisy machine since it is essentially a stationary magnetic structure with an air-gap. It is almost impossible to machine the parts so that the rotor is absolutely concentric with the stator bore. Any deviation from the central position will cause the magnetic field to become unbalanced, producing pulsating forces which cause the machine to vibrate. The bearings are made as close fitting as possible to reduce vibration to a minimum. Mr. B. G. Lamme's patent No. 740147, covering polyphase induction regulators, describes a taper sleeve-type bearing designed to be adjustable to keep the bearing close fitting. This type is difficult to manufacture and requires a skilled mechanic to adjust it

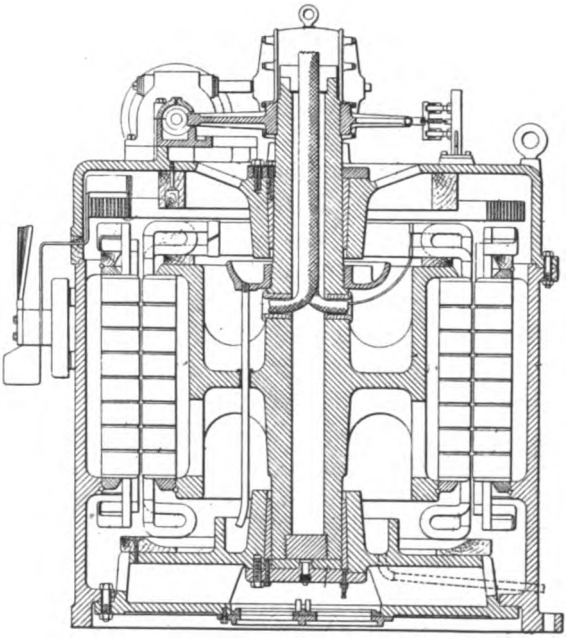

FIG. 10 (a)—THE REGULATOR OF FIG. 10 IN CROSS-SECTION

properly. The tapered sleeve bearing has been replaced on the modern machine by a tapered roller bearing which gives practically zero clearance, adjusts itself for wear, has permanent alignment and is free turning.

*See "Insulation and Winding Induction Regulators" by R. E. Dawe in the JOURNAL for Aug. 1927.

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The tendency in design is toward small diameter and tall machines. This tendency results from the location of the regulators in service and the desire to produce the most economical machines. The regulators are usually located in substations where floor space is at a premium, or are used to increase the capacity of a feeder already installed, where no room has been allotted for a regulator. The cores of the larger diameter machines cost less to assemble than small diameters, but they require larger and more costly brackets and tanks. Also more oil is required for the cooling medium, since the radiating surface for a given loss varies as the diameter times the height, while the output is a function of the square of the diameter and the height. As an example, if the volume of active material and also area of cooling surface for a regulator are assumed constant for a given rating, doubling the diameter and reducing the height to one-half will double the volume of the tank and therefore more than double the required amount of oil.

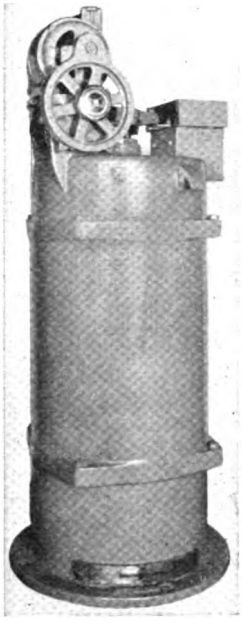

FIG. 11—A MODERN, AIR-COOLED INDUCTION REGULATOR

The small diameter machines have a greater tendency to vibrate than machines of larger diameter since the shaft diameter is more limited, and also since the distance between bearings is greater than for the larger diameter machines. Ordinarily, the distance between bearings is governed by the height of the tank, since one bearing is placed at the bottom and the other in the top cover. This apparently serious handicap has been ingeniously overcome on single-phase regulators by the addition of a third or middle bearing placed just above the windings. This bearing not only reduces the distance between bearings to a minimum but also changes the shaft from a simple two-support beam to a continuous beam whose deflection for a given load is less than for a simple two-support beam of similar proportions. This results in a quiet machine.

The torque on the rotor of a single-phase regulator is the resultant of the torque due to the interaction of the primary flux and secondary current, the secondary flux and primary current, the secondary flux and short-circuited winding current and the tooth torque. The torque due to the primary flux and secondary current depends upon the phase angle between the two and the position of the rotor, and may be considered the fundamental torque of the regulator. With the regulator in the mid-position, at unity power-factor, the secondary current is a maximum when the flux is zero and the torque is zero; while at zero power-factor the secondary current and the flux reach a maximum at the same instant, so that the torque is a maximum. At both maximum boost and buck positions at any power-factor, the torque is zero since the secondary current does not lie in the field. The torque due to the interaction of the secondary flux with the primary current and short-circuited winding are in opposite directions and would cancel each other if the windings were fully distributed. However, since they are not fully distributed a small torque results in certain positions of the rotor.

The tooth torque is dependent upon the design of the teeth and as the number of teeth is usually small it is difficult to eliminate this torque by changing slot and tooth widths. This torque is usually of little consequence on small machines of standard 60 cycle frequency. On large machines, and machines of low frequency, the tooth torque may cause the rotor to vibrate torsionally, which may in turn cause lateral vibrations. This can be overcome by skewing either the rotor or stator, entirely eliminating the tooth torque.

The above features in design have reduced objectionable vibration to a minimum; in fact, the present-day induction regulators are in general as quiet as other alternating-current apparatus of the same physical size.

The success and popularity which the induction regulator has enjoyed is due, in a large measure, to the accessories which are used to control the regulator automatically. The development of the combined motor and brake, voltage regulating relay, motor reversing switch and compensator has kept pace with the feeder regulator and forms another interesting story.

Induction regulators are similar to transformers in that they can be built air-cooled, oil-insulated oil-cooled, and oil-insulated water-cooled. They have the limitations of motors and generators, however, in that they are of slotted construction, and, therefore, difficult to build for high voltage and low capacity. They have been built in sizes from 2 to 1750 kv-a three-phase and from 0.5 to 500 kv-a single-phase. Induction regulators have also been used for many applications other than for feeder-voltage regulation. They have been used for testing sets, supplying variable voltage for laboratories, regulating the speed of motors, regulating the applied voltage to electric furnaces, and many other applications.

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# Protective Grounds*

V. E. JOHNSON

FREQUENT reference has been made to pipe or driven grounds. These are inexpensive and convenient and will, if properly installed, serve almost every requirement. Ordinary galvanized iron pipe is very commonly used, though a number of patented rods are available under various trade names. Galvanized pipes are preferable to black pipes because they last longer and because the connections to them can be more easily made, but electrically they have little advantage. Rust does not interfere appreciably with the passage of the current, as the moist iron oxide in contact with the earth has low resistance. If black pipe is used, it must of course be unpainted and free from grease.

To facilitate driving, the lower end is sometimes flattened out into a chisel shape, and sometimes equipped with a separate driving point. Either of these presents some advantages in stony soil, but in ordinary earth the pipe goes down almost as readily with the square open end.

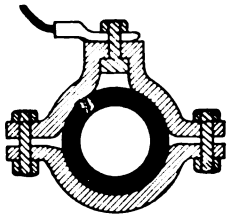

FIG. 6—A SPECIAL GROUND PIPE CONNECTION

Sometimes the upper end is equipped with a heavy driving cap to prevent splitting and crushing. It is not uncommon, however, to drive the plain pipe, letting it crush somewhat, and cutting and threading it afterward, using either a plain cap or a connection cap. If the soil is very hard and stony, it may be necessary first to make a hole with a steel bar of slightly smaller diameter than the rod to be driven. A driving point on the rod will be of service under such conditions.

The ground wire can be attached in various ways, in addition to the connection caps. It can be doubled back on the pipe, wrapped with copper wire and carefully soldered. A plug can be driven into the end about two or three inches, and a loop secured by means of type metal or solder. A capped pipe can have a hole tapped in the top and an ordinary soldered lug used. This has the disadvantage of being an expensive installation and there is also the possibility of loosening if the rod or wire moves. A special pipe clamp can be used, as in Fig. 6. Of these methods the pipe plug and solder method is probably as cheap and effective as any.

The top of the ground rod should be driven slightly below the ground level, and the cap and connection painted with asphaltum paint to prevent electrolytic corrosion between the copper and other parts. At this depth the connections can readily be inspected and are still not apt to be displaced by traffic. If the lead is on a pole, it should be covered with a moulding both at the ground and at the top. The lower guard should extend slightly into the earth to prevent contact and damage by passers by. The upper one reduces somewhat the risk to linemen. The portion between should be securely stapled to the pole.

To facilitate routine testing, some type of connector as that in Fig. 7 may be used. These are cheaper and more convenient than a soldered joint.

If the ground rod is found to have too high resistance, a second one should be driven, as far from the first as the local conditions permit—six to ten feet if possible. On transformer settings, spacing can be obtained by driving rods on opposite sides of the pole, though there is some loss of effectiveness due to the insulating action of the pole. Some operating companies use a minimum of two grounds regardless of the resistance. Still lower resistance can be obtained by multiple grounds. These are usually arranged in a circle.

On account of space limitation imposed by sidewalks, curbings, or pavements, this may not always be possible, and again, under unfavorable conditions, the number of rods required may be too great. In that event, resort must be had to chemically treated grounds. Solutions of salt, copper sulphate or common washing soda are infiltrated into the soil adjacent to the rod, and being of good conductivity, reduce the ground resistance to a remarkable degree. Salt is perhaps the most commonly used, but its corrosive effect makes it somewhat less desirable than copper sulphate. Copper sulphate costs more per pound, but as less of it is required the cost is not much different. Experiments have shown that copper sulphate is not only non-corrosive in itself, but also that it tends to coat the ground

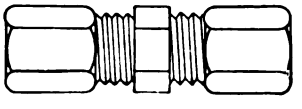

FIG. 7—A SIMPLE CONNECTOR FOR MAKING GROUND TESTS

pipe with copper, which further lengthens its life. Salt has the advantage of attracting and retaining moisture, and of lowering the freezing point, so that the effectiveness is unimpaired, even in very cold weather or during prolonged droughts.

Several methods of applying the ground treatment are in use. One is to bore a hole about three or four feet deep with a fence auger, fill this about three-fourths of the way up with salt or copper sulphate, and then drive the ground rod through this pit and into the earth beneath, as in Fig. 8 (a). Sometimes the hole for the salt is made by driving a big pipe into

*Continued from the JOURNAL for Aug. 1928, p. 384.

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the ground instead of by using the auger. On other installations the salt pit is made wider at the top as in Fig. 8 (b), so as to hold more salt. In any event, the ground must be thoroughly wetted down.

Neither salt nor copper sulphate last forever, and the ground must in time be re-treated. After treatment the resistance becomes gradually less as the treated water seeps farther and farther into the surrounding soil. In time, however, the chemicals dissipate themselves entirely, to the accompaniment of a gradual increase in resistance.

In making the final test of a ground after treating, sufficient time must be allowed for the solution to saturate the surrounding earth thoroughly. This will usually require 24 hours or more.

### BURIED GROUNDS

For station arresters, and for feeder grounds which may be required to dissipate large amounts of energy, multiple pipe grounds may often be used. Ordinarily there are no serious space limitations in a substation, so that wide spacing is readily obtained. The bonding conductors may consist of stranded cable laid in shallow trenches, or of bus copper attached to the structural steel members or to the cement foundations.

Under adverse conditions it may be impossible to obtain sufficiently low resistance even with treated multiple grounds, or the soil may be so stony as to practically preclude the driving of the pipes. Resort must then be had to buried grounds. A simple, and yet effective method is to bury a mass of old trolley wire in a bed of crushed coke and salt well below moisture level. Intimate contact is obtained by tamping the coke very tightly around the wire, and watering the pit liberally. A small sewer tile plugged at the top can be installed to permit the convenient addition of salt or copper sulphate.

A more workmanlike job is obtained by using standard cast iron or copper ground plates in place of the junk wire. The surface should be some three to five square feet. In order to secure good contact be-

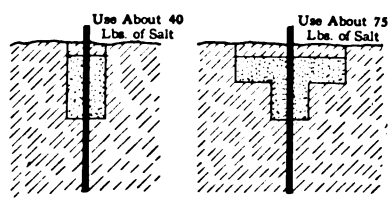


FIG. 8 (a) AND (b)—SIMPLE AND EFFECTIVE TREATED GROUNDS

tween the ground lead and the plate, a number of connections should be used. These may consist of pieces of heavy copper bent and soldered to the cable. An elaborate ground is shown in Fig. 9, where two plates are buried in coke pits treated with salt or copper sulphate, with two separate ground leads from each to the ground bus at the surface.

Inasmuch as the danger of electrolysis is always present, it is desirable to confine this to the comparatively large masses of metal in the ground plates themselves, and to protect the leads as much as possible. A cheap and effective way to do this is to bring the leads to the top through ordinary rubber garden hose. This will last a surprisingly long time, and will eliminate much trouble.

In hilly countries the substation may be so far above the permanent moisture level as to make the cost of buried grounds prohibitive. In that event one or

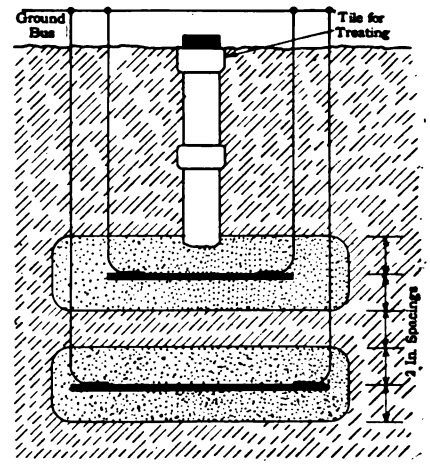


FIG. 9—ARRANGEMENT FOR AN EFFECTIVE BURIED GROUND

more regulation pipe wells may be installed. Cases are on record where a depth of almost 100 feet was needed in order to obtain the required low resistance. By using slotted or perforated pipe for the lower sections, soil treatment can be introduced through the well casing. A saturated solution is poured into the opening and either forced through the perforations by air pressure applied at the top, or left to seep in of its own accord. Ice cream salt or crushed copper sulphate is then dumped into the pipe in sufficient quantities to maintain the conductivity for considerable periods of time. Care must be taken in treating such deep ground wells (or in any installations, for that matter) that the chemicals do not contaminate the drinking water in nearby wells.

The most difficult locations for obtaining good grounds are in mountainous countries where substations are installed on rock that is bare, or at the best only thinly covered with earth. If the station is extensive, use may be made of an artificial ground, analogous to the now so common counterpoise used in radio, consisting of the bonded together major masses of metal, such as structural steel towers, machine frames and the like, and drained by connection to as good a driven or buried ground as it is possible to obtain.

The adequacy of these artificial counterpoise grounds is, however, doubtful, and their limitations should be recognized. The alternative is to run grounding cables to some point where a satisfactory connection can be obtained.

### WATER PIPE GROUNDS

In grounding to water pipes, care must be taken that the tap is made at a point which will not be iso-

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lated from the mains. It is therefore preferable to make the connection on the street side of the water meter, though this is not really essential, providing jumpers around the meter are permanently attached, so that its removal will not affect the ground circuit.

There is some question as to the conductivity of bell and spigot joints in street mains—but inadequacy in this respect is exceptional. If, however, a line of this type is laid in the open, i.e., not buried, it may be necessary either to bond the joints to each other from the tap to the point where they enter the earth, or to parallel it with a grounding cable for the necessary distance.

Ground taps to water pipes are either of the clamp type, or of the plug type. In the former, a metal strap is fastened tightly about the pipe, after it has been thoroughly cleaned. To this strap the ground lead is either soldered or bolted. In the presence of moisture, such a connection should be coated with asphaltum paint.

Taps of this type, even when carefully made, may deteriorate due to corrosion between the strap and the pipe. A plug tap will not be so apt to fail, but its installation may be difficult.

If brass fittings of a permanent nature are accessible, it may be possible to utilize these in making a soldered joint.

Taps to hydrant risers are made by using a soldered lug clamped to the lower half of the underground flange by one of the bolts. The lug and bolt should also be covered with asphaltum paint. The wire should preferably be enclosed in a pipe of rubber hose, and should be guarded on the pole by a moulding extending well below the surface of the earth.

If taps must be made to water mains under pressure, and hydrant risers are not available, the leads can be attached to corporation cocks or special brass plugs installed with a pipe tapping machine.

### TESTING GROUND RESISTANCE

Frequent reference has been made to the importance of determining the resistance of ground connections, at the time of installation, and at routine periods thereafter. A rigid solution involves complex relations between a number of variables, and a refinement of procedure that is commercially impossible. Fortunately, the inaccuracies due to the simpler approximate methods are not serious, and in any event the purpose of the test is merely to determine whether or not a pre-determined safe value has been exceeded.

The testing procedure is determined to a considerable extent by the available equipment, and by the general conditions under which the tests must be made. The minimum of apparatus consists of a voltmeter and ammeter, but better results can be obtained by the use special ground testing instruments, of which several types are obtainable.

It is always better, and usually more convenient, to use alternating current in making the ground tests. There are, however, conditions in which direct current must be used, due to the lack of facilities for obtaining alternating current of suitable voltage. In order to avoid errors due to polarization, which increases the apparent resistance, the readings must be made quickly, and checked with a reversed direction of current flow. In the absence of other sources, radio *B* batteries may be used, but their very low current capacity preclude their use except for very approximate measurements.

The drop of potential method of resistance measurement makes use of a voltmeter and ammeter, and is therefore sometimes known as the voltmeter-ammeter method. The readings obtained are substituted in Ohm's law.

$$Resistance = \frac{Volts}{Amperes}$$

For example, if the voltmeter and ammeter read 80 volts and 10 amperes respectively, the resistance would be 8 ohms.

It can be applied to a number of testing procedures, of which only three are given here. The first uses a water system ground as a standard and assumes that it is of negligible resistance. This assumption must not be loosely made, for, as has already been pointed out, its truth depends entirely upon the magnitude and

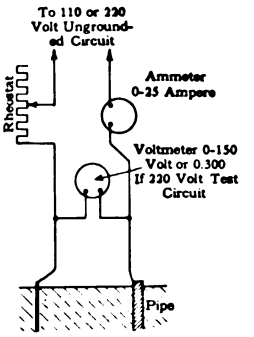
To 110 or 220 Volt Ungrounded Circuit
Ammeter 0-25 Ampere
Rheostat
Voltmeter 0-150 Volt or 0-300 If 220 Volt Test Circuit
Pipe

FIG. 10 — CIRCUIT ARRANGING FOR GROUND TESTING

general characteristics of the pipe system, as well as upon the location and connection of the ground wire.

The arrangement of the testing apparatus is shown in Fig. 10. The rheostat is used to keep the testing current within the range of the instruments, and prevents the blowing of the fuses in the test circuit. If there is any question as to the testing circuit being free from grounds, a suitable insulating transformer must be used.

The rheostat shown may be replaced by a two or three step resistor consisting of ordinary 550 watt, 110 volt, heating elements. The current should be adjusted to some convenient value, such as 10 amperes, and simultaneous readings taken on the voltmeter and ammeter. The resistance so obtained represents the sum of the artificial and water pipe grounds as well as the connecting leads, so that the true value is lower than that derived from the calculation.

The possibilities of error in the previous method, and the difficulty in making satisfactory connections to water pipe reference grounds has led to its gradual abandonment in favor of other schemes, one of the most common being the three point test. This utilizes two additional grounds (temporary, if necessary) in-

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stalled with a spacing of preferably 15 to 20 feet, and located so as to form roughly an equilateral triangle.

The spacing and arrangement requirements are, however, not very rigid, so that the electrodes of a multiple ground may be used, even though the spacing is only six to ten feet. On the other hand, it is quite important that the three grounds have about the same resistance, so that it would be undesirable for example to use a water system connection in conjunction with two driven rods.

Tests are made between the electrodes in pairs, each determination giving the resistance of two in series. The actual procedure is exactly the same as that used in the previous method, after which a simple calculation is made, as shown by the following example:

EXAMPLE: Designate the three grounds as *A*, *B*, and *C*, and assume test values as follows:

| Points | Volts | Amps | Ohms |
|---|---|---|---|
| *A* to *B* | 80 | 16 | 5 |
| *B* to *C* | 84 | 12 | 7 |
| *A* to *C* | 81 | 9 | 9 |

Then solve for individual values as follows:

Resistance of $A + C = 9$ ohms.
Resistance of $A + B = 5$ ohms.
Subtracting, $C - B = 4$ ohms.
From test $C + B = 7$ ohms.
Adding, $2C = 11$ ohms.
$C = 5.5$ ohms.
Then $A = 9 - 5.5$ ohms or 3.5 ohms.
and $B = 5 - 3.5$ ohms or 1.5 ohms.

The values may also be found by substituting in the following formulas:

$$A = \frac{(A + B) + (A + C) - (B + C)}{2}$$

$$B = \frac{(A + B) + (B + C) - (A + C)}{2}$$

$$C = \frac{(A + C) + (B + C) - (A + B)}{2}$$

If the three rods form a multiple ground, its total resistance will be the reciprocal of the sum of the individual reciprocals. Hence the total resistance is,—

$$\frac{1}{\frac{1}{3.5} + \frac{1}{1.5} + \frac{1}{5.5}} \text{ or } 0.088 \text{ ohms.}$$

There is a possibility that the three electrodes may be in a small conducting pocket of soil quite isolated from the earth itself, but, except in mountainous regions, this is a remote contingency. Only a knowledge of the surrounding topography can avoid erroneous conclusions due to such abnormalities.

In order to simplify the three point method and to permit the measurements to be taken with only one set up, a number of test boxes have been designed. These vary in construction details, but consist, in general, of a panel upon which are mounted test terminals and switching devices for conveniently taking the required readings.

The third method, frequently referred to as the two electrode test, uses a scheme of connections such as that shown in Fig. 11. The voltage from the insulating transformer is impressed upon the ground under test, $G_t$, and a reference ground, $G_r$. The voltmeter $V$ is then used to measure the difference of potential between the rod and a voltage probe $P$ driven into the ground a distance of some 10 or 15 feet away from either ground rod. The resistance is then obtained by the formula previously given, $R = E/I$.

This method permits a direct determination of the resistance, and considerable time can be saved by its use. There is, however, a possibility of error, due to the fact that the contact resistance between the voltage probe and the earth may be a considerable portion of the instrument resistance. This can be readily checked by using a voltmeter having a high and low scale, and reading the potential difference on each of them. If the readings are the same, the probe resistance is negligible. The same result can be used by using separate meters having different internal resistances.

If the probe resistance is of sufficient magnitude to affect the accuracy of the results, the method can still be applied by using the following comparatively simple procedure. First measure the drop between the probe and each of the two ground rods. Designate these values as $G_r$ and $G_t$ respectively. Then the resistance of $G_t$ will be $\frac{G_t \times \textit{Line Voltage}}{I\,(G_t + G_r)}$. The line voltage is that impressed across $G_r$ and $G_t$.

EXAMPLE: Assume that with 100 volts applied across $G_t$ and $G_r$, the potential drop to the probe is 35 volts and 45 volts from $G_t$ and $G_r$ respectively. With a current flow of 10 amperes, the resistance of $G_t$ is $\frac{35 \times 100}{10 \times (35 + 45)}$ or 4.75 ohms.

Any of the test methods given above entail considerable trouble and expense, and on routine testing

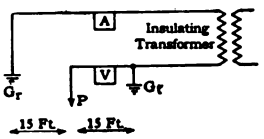


FIG. 11—CIRCUIT ARRANGEMENT FOR TWO ELECTRODE METHOD OF GROUND TESTING

require the transportation of considerable apparatus. To eliminate this cumbersome procedure, there have been developed and marketed a number of self-contained ground testers. These consist of a hand-driven generator for supplying the necessary current, and a direct reading ohmmeter. The testing is carried out by either the three point or two electrode method, the latter being preferable. The voltage element of the ohmmeter is designed with a very high resistance, so that the possibilities of error due to the use of the voltage probe are minimized. The testing current is alternating, and of a non-commercial frequency, in order to eliminate errors due to the existence of stray currents in the area under test.

## CONCLUSION

It is very evident that hap-hazard installation will result in unsatisfactory grounds, and that inspection alone is not sufficient to determine their adequacy. Plentiful moisture does not necessarily indicate low resistance, nor can depth or surface area be used as a criterion. At the final analysis, only actual tests can determine whether or not any given ground will provide proper protection against the hazards of abnormal voltages.

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# Fluid Governors for Prime Movers

## VI--Remote Control

HENRY F. SCHMIDT

FOR the reason that the connecting link between the rotating shaft and the operating mechanism in the governors under discussion is fluid, and the spring which fixes the speed is stationary, and therefore adjustable while the apparatus is in motion, these governors lend themselves particularly well to remote control. Further, since the speed is varied either by changing the tension of the governor spring, or by varying a pressure, they are in general more susceptible to minute variations than electrical devices, since the latter usually depend upon a limited number of points on a rheostat, or changing the number of poles in a motor.

Two general types of remote control are given here,—one with control by the primary fluid, and the other in which a secondary fluid is employed.

Referring to Fig. 35, it is obvious that the spring-loaded relief valve on the lower part of the operating cylinder, could be removed to any place desired, as for instance the switchboard gallery, and connected to the operating cylinder by a pipe. The speed of the turbine could then be controlled by the switchboard

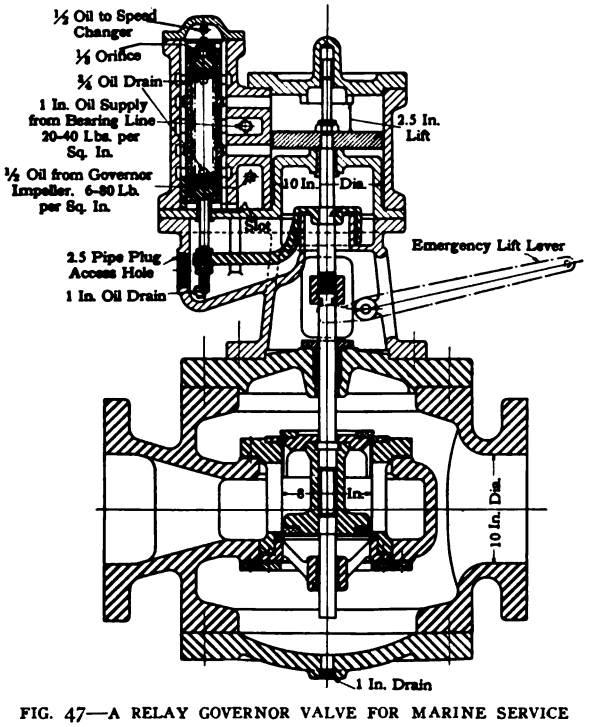
½ Oil to Speed Changer
⅛ Orifice
¾ Oil Drain
1 In. Oil Supply from Bearing Line 20-40 Lbs. per Sq. In.
½ Oil from Governor Impeller. 6-80 Lb. per Sq. In.
2.5 Pipe Plug Access Hole
1 In. Oil Drain
2.5 In. Lift
10 In. Dia.
Emergency Lift Lever
8 In.
10 In. Dia.
1 In. Drain

FIG. 47—A RELAY GOVERNOR VALVE FOR MARINE SERVICE

operator for synchronizing. The same principle is employed in the remote control shown in Figs. 47 and 48, which are the governor valve and remote control stand, respectively, of a marine turbine installation. In the governor valve mechanism of Fig. 47, the governor oil is admitted below the relay valve sleeve piston. This tends to force the relay valve up against the tension of the spring, which is attached to the relay valve at its upper end and, through a stem, to an arm attached to the operating piston rod at its lower end. Oil for operating the valve is supplied from a separate source to the central part of the relay valve sleeve. The pipe connection to the control stand is connected

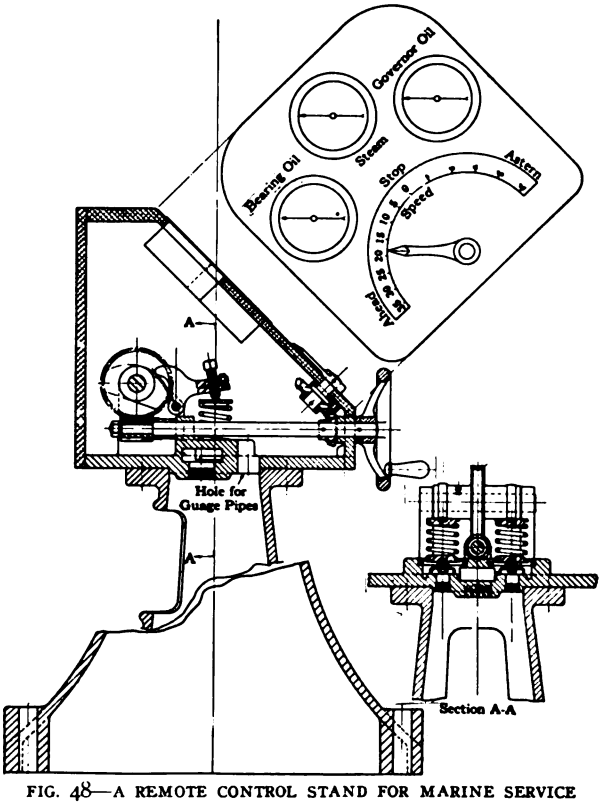


FIG. 48—A REMOTE CONTROL STAND FOR MARINE SERVICE

to the space above the relay valve sleeve, a small hole through the top of the relay valve permitting the oil to leak into this space.

Assuming the valve in the open position (not as shown) and a fixed constant pressure above the relay valve, the turbine would speed up until the pressure developed by its impeller is such that the difference in pressure below and above the relay valve is sufficient to raise the sleeve and admit oil above the operating piston, forcing it down until the stretch of the spring is such as to pull the relay valve sleeve down just enough to cut off the supply of oil to the operating cylinder. Now, if the turbine speeds up, the relay moves up and admits oil above the piston, closing the valve, and vice versa.

In this arrangement, the governing between zero speed and full speed is not between zero pressure and maximum pressure, since a small constant pressure of six to ten pounds is required under the relay valve to hold it up when the steam valve is closed. The governor pressure never falls to zero, however,

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since the pressure maintained at the impeller inlet by the ejector or auxiliary oil pump never falls below about ten pounds.

In a marine installation, one control valve is required for ahead operation, and one for astern. The control pipe from the space above the relay valve sleeve of both the ahead and astern valves is led to the remote control stand, Fig. 48, which may be located any place desired.

The control stand consists simply of two spring-loaded relief valves, one for ahead and one for astern, to which the control pipes are connected. The tension of the relief valve springs is varied by cams and bell cranks movable through a worm and wheel by the operating wheel and handle on the front of the stand. The cams are spaced 180 degrees apart, so that one is in the shut position when the other is in use. A pointer is geared to the operating shaft, which permits setting the speed exactly to that desired.

Set in the face of the stand above the indicating dial, are the bearing oil pressure, steam and governor oil pressure gauges. The governor oil gauge is graduated in revolutions per minute and its reading will always check with the speed to which the hand wheel pointer has been set. This gauge is a great help in making fine adjustments of speed to maintain position when steaming in formation.

The oil impeller and pressure gauge constitute the most rugged, reliable and accurate tachometer for continuous operation yet devised. While it is subject to slight error due to change of oil temperature, these changes are generally so small in normal operation that they may be neglected. It may be urged that pressure gages are not reliable, and this is of course, true when subjected to sudden changes of pressure and temperature. It is not true of well made gages used as tachometers where the pressure changes are always gradual and the gages are subjected only to small changes of temperatures.

For use in conection with the oil governors on underfeed stoker drives, the gages are graduated in r.p.m., pounds of coal per hour, and percent of boiler rating which has resulted in increased economy because of better regulation of the rate of firing.

A purely mechanical remote control is illustrated in Fig. 49. This control is intended for various mechanical drives, such as paper mill, blowers, pumps, etc. Two governors and steam chests for independent turbines are shown, each governor consists of a piston and spring controlling the admission valve. Each operating cylinder is connected to the impellent chamber of the turbine which it controls through the high-pressure oil line *A* and the leakage past the piston is returned to the reservoir by the drain *B*. The tension of the governor springs is varied by revolving the spring screw or piston rod *C* by means of the spur gears *D* and *E*. These gears are loosely fitted so as to permit free sliding of the gear attached to the piston. The gear *E* is carried by a shaft *F* which carries a pair of bevelled gears *G* and *H*. An extension of the shaft *F* is carried to the point from which control of the turbines is desired, where a hand wheel and indicating dial are located.

The two governors are interconnected by an extension shaft by the bevelled gears *G* and *H* of the two governors. Thus when the position or spring tension of one governor is altered the same change is made in the governor of the other machine. This is regardless of whether one or both of the machines are in operation. Since the oil pressure delivered by the impeller is directly proportional to the square of the speed, and since the load on the spring is always directly proportional to the elongation, it will be obvious that any means of measuring the stretch of the spring may be employed to indicate the oil pressure acting on the piston; or in other words the speed at which the turbine is running. The indicating dial located at the control point is graduated in r. p. m., which makes it possible for the operator to set the speed of the turbine as desired. Also, in the case of such drives as pumps, blowers, and other machinery where the load is proportional to some function of the speed, the indicating dial may further be marked to show the proper nozzles to have open to obtain the best economy.

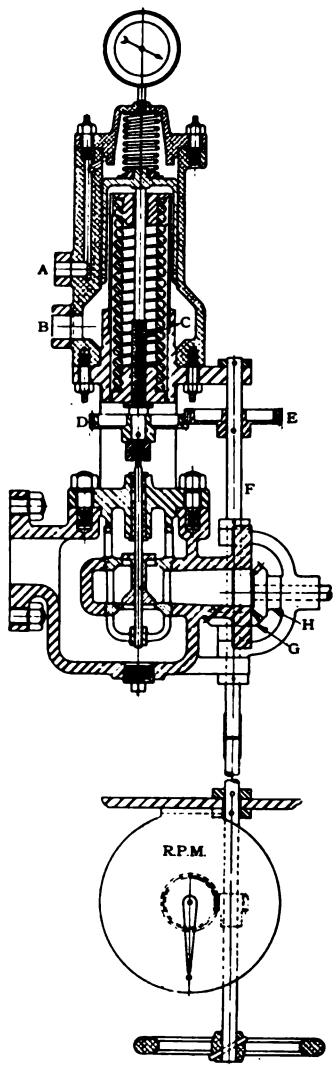


FIG. 49—A MECHANICAL REMOTE CONTROL ARRANGEMENT

The paralleling of blowers is rather a delicate operation as it is necessary to bring the blower being started up to substantially the same speed as the blower or blowers in operation before cutting it into the duct, since the pressure must be substantially equalized before they are connected in parallel. Where two or more blowers are driven by turbines equipped with this mechanical remote control system, this difficulty is obviated, since all the governors are always set for the same speed regardless of whether the turbines are running or not. Therefore, if one blower

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is in operation and it is desired to cut in another blower, it is only necessary to open the throttle valve and the blower automatically comes to the same speed as the other one. This same mechanical method of interconnecting turbines may be applied to any number of units, and provision for remote control from several stations may likewise be provided.

Where it is desired to have one turbine increase in speed faster than the other, it is necessary only to make the scale of one of the governor springs greater or less than that of the other, since the rate at which the speed increases for a given stretch of the spring is, of course, dependent on the scale. Where the speeds are to be exactly the same and increase at the same rate, the scale of these springs must be made equal. This can be done by adjusting the springs on the governor shackle nuts.

A remote control system for forced draft blowers is shown in Fig. 50, in which the control is through a secondary fluid,—air, in this instance. The control consists of a master controller, switching valves and

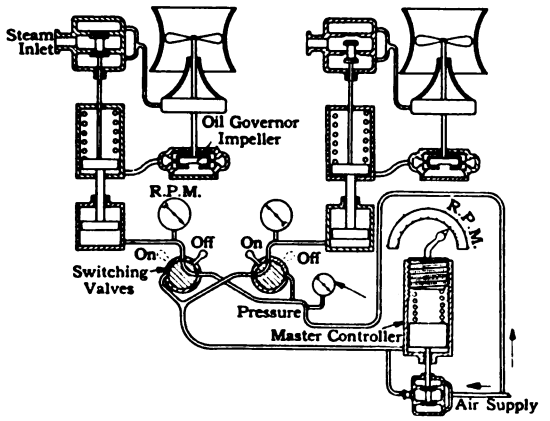


FIG. 50—A REMOTE CONTROL ARRANGEMENT FOR BLOWERS

air cylinders which work against the springs of the oil governor operating cylinders.

Each of the blower turbines is equipped with an oil impeller, operating cylinder and governor valve, in addition to which there is an air cylinder and piston which is connected to the oil-operating piston. Oil governors are adjusted so that the different turbines run at the same speed when no air pressure is admitted to the air cylinders.

Since the turbines must run fast enough that the oil impellers will build up sufficient pressure to compress the governor springs and partly shut off the steam valves, it is seen that, if air pressure is admitted below the air piston, these will assist in compressing the springs, so less oil pressure is required, resulting in the turbines slowing down until the sum of the oil pressure and air pressure multiplied by the respective piston areas is equal to the spring load. If the air pressure is increased sufficiently, the steam valve will be closed and the turbine stopped.

The master controller is simply a spring-loaded graduated, constant-pressure valve which, as indicated, may be set for any speed desired. The air from the master controller passes through a manifold of three-way switching valves, there being as many switching valves as there are turbines. A direct line from the high-pressure air supply also goes to the switching valves.

In Fig. 50, the left-hand switching valve is in the *off* position connecting the air cylinder of the left-hand turbine directly to the high-pressure supply line. The right-hand switching valve is in the *on* position, connecting the air cylinder of the right-hand turbine to the master controller. With this system, the throttle valves on all the turbines are always kept open, being started and stopped by the switching valves from the central control station.

When the switching valve of the left-hand turbine is thrown to the *on* position, since there is no oil pressure under the oil piston, the governor valve will go wide open and the turbine will accelerate rapidly until the oil pressure is exactly the same as in the right-hand turbine. That is, the mere operation of throwing the switching valve to the *on* position, synchronizes the machine started with all others in operation. This is a very valuable feature, for the control of a number of blowers operating in parallel.

In this arrangement, the turbine speed decreases as the air pressure is increased. This is advantageous for some classes of service, such as blowers, since these rarely are required to operate below one-fifth full speed, and the most sensitive control is required at high speed, in which case the air pressure is low and a slight variation of the controlling air pressure has practically no effect on the speed, so small variations in the air pressure due to variations in the source of supply are not noticeable.

In all the previously discussed fluid-operated speed changers and remote-control methods, the load on the piston was varied by increasing or decreasing the oil pressure on top of the piston, thus assisting the action of the governor spring. In Fig. 51 a remote control is shown in which the speed is varied by increasing or decreasing the pressure of the oil supplied to the inlet of the impeller. This control was worked out particularly for some small air-operated turbines used for reeling artificial silk. The turbines range from one-tenth to about one horse-power capacity at speeds from 6000 to 18 000 r.p.m.

The requirements for this service are as nearly constant speed as possible. Furthermore from 50 to 150 turbines must be regulated from a single control, and all operated within a few tenths of one percent of the same speed. Obviously, since the power is almost entirely absorbed in windage and bearing friction, and since the speed must vary slightly to change the position of the governor valve; in order to get constant speed within the small limit required, the bearing friction of all the turbines operated from one control should be as nearly as possible substantially the same, and all friction in the governor mechanism

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must be eliminated. These results are accomplished by the arrangement illustrated in Fig. 51, which shows a cross-section of the turbine, and a diagramatic arrangement of the complete system.

The lower end of the turbine spindle carries an impeller *A*, which delivers oil under pressure to the piston *C*, which operates an unbalanced needle-type valve *D*. The governor springs are all calibrated to the same scale, and adjusted to operate at the same speed at the same oil pressure.

Oil is supplied to all impellers from a central oil reservoir by means of the oil pump *G*, and the speed is varied by changing the pressure of the oil delivered to the impeller by means of the speed-changer relief valve *I*, which is graduated in r.p.m., so that the pressure can be set to operate the turbines at any desired speed. The oil supplied to the impeller also furnishes oil for lubricating the turbine bearings. Obviously, since all the turbines are operating from a common reservoir the temperature, viscosity and lubricating

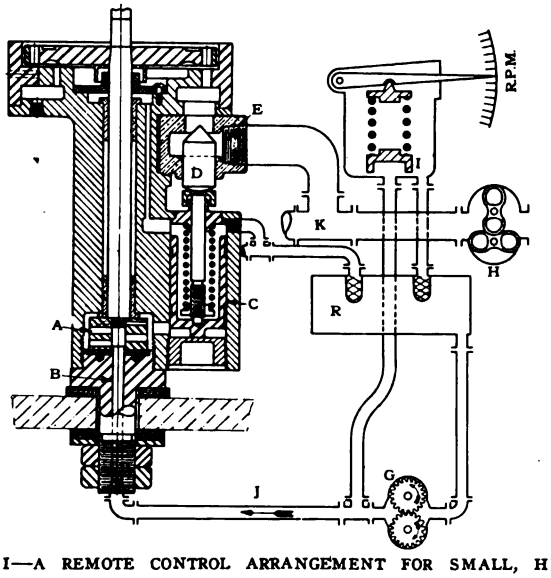


FIG. 51—A REMOTE CONTROL ARRANGEMENT FOR SMALL, HIGH-SPEED TURBINES

properties of the oil supplied to all the bearings is the same, thus insuring substantially equal bearing friction, and freedom from temperature effects on the governors of all the turbines. The air for operating the turbines is supplied from a single motor driven Roots or Connelsville type of blower, which delivers the air at a slightly pulsating pressure. These pulsations of pressure act on the unbalanced needle governor valve, imparting a slight oscillatory motion to the valve and governor pistons, thus eliminating the friction. Such pulsation is imperative in machines which operate continuously at approximately constant load, since under these conditions the governor valves would remain in substantially a fixed position without any movement to keep them loosened up. This application illustrates the field covered by the oil governor, since on small turbines at such high speeds, any other type of governor would be almost a practical impossibility.

Where accuracy of control and definite speed for a given control setting are not required, the gear-type governor may be employed, such as shown in Fig. 52 in which *P* is the gear oil pump, driven by the main shaft either directly or through gearing, which delivers oil to the governing piston and through a relief valve *V* which constitutes the remote control feature. This is an adaptation of the valve in Cartwright's patent.

Since the pressure delivered by a gear pump depends upon the revolutions and the size of the discharge orifice, it is obvious that the pressure can be varied by varying the size of the discharge orifice.

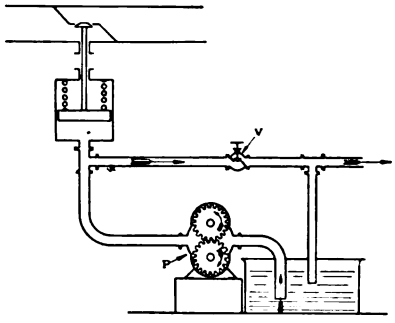


FIG. 52—A REMOTE CONTROL FOR A GEAR TYPE PUMP

Thus, if the valve *V* is partially closed, the pump will tend to deliver a higher pressure and close the governor valve, slowing down the turbine until the quantity of oil, delivered by the pump, is such that just sufficient pressure is maintained to admit sufficient steam to the turbine to maintain the required speed. The overflow from the valve *V* goes back to the reservoir, or may be used for lubricating the bearings.

One of the possibilities of the oil governor closely related to remote control is shown in Fig. 53. Here a main generating unit and a house turbine are shown, the house turbine furnishing steam for heating the condensate from the main turbine to a constant tem-

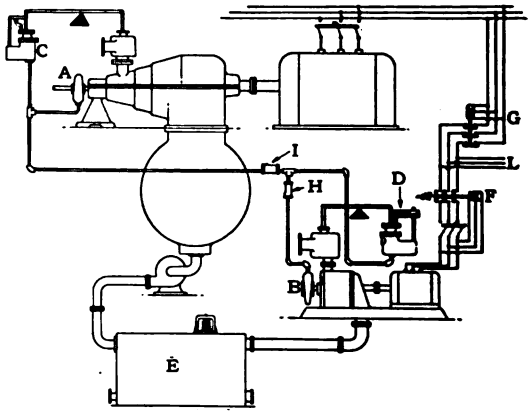


FIG. 53—A REMOTE CONTROL FOR AN AUXILIARY TURBINE

perature. This is accomplished by varying the steam admitted to the house turbine in direct proportion to the steam admitted to the main unit; whence it follows that the discharge temperature of the condensate also is constant.

This result is secured by interconnecting the two oil governors on the main and house turbine units. There is an oil impeller *A* on the main turbine, Fig. 53, and an impeller *B* on the house turbine, the latter

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being made of such a diameter that at normal speed it gives a pressure slightly less than that of the impeller on the main turbine. Each turbine is equipped with a relay operating mechanism, that on the house turbine being of the type shown in Fig. 24, fitted with an adjusting cam so that any desired relationship between the position of the steam admission and the relay valve can be obtained. In normal operation, the admission of steam to the house turbine is controlled by the impeller *A* on the main unit through the interconnecting pipes between the two impellers and operating mechanism. The check valves *I* and H are inserted in the pipe lines so that in the event of the main units shutting down, the house turbine would continue to operate at a slightly increased speed, but would function otherwise in a normal manner. A circuit breaker and reverse current relay are shown at *F* and *G*, so that if the power goes off the main bus, the house turbine will continue to operate independently.

The cam arrangement on the house-turbine operating mechanism shown at *D* permits variation of the

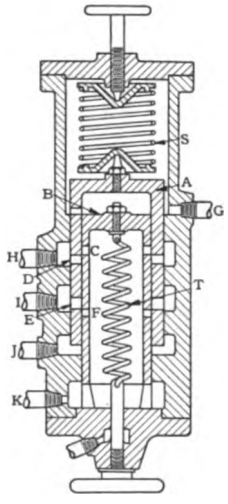


FIG. 54—A PRESSURE CONVERSION ARRANGEMENT

admission of steam to the house turbine so as to maintain any desired relationship between the steam admitted to the main unit and to the house turbine. Thus these may be maintained in direct proportion to each other; or the steam admitted to the house turbine may be made to increase slightly more rapidly than the steam to the main unit; or vice versa; so that the temperature of the condensate discharge may be maintained constant or even given a rising or falling temperature characteristic with increase of load on the main unit.

In place of the auxiliary turbine driving a house generator, this turbine might drive a circulating pump, or other load, and the governor be so adjusted as to maintain the discharge water from the condenser at a constant temperature or to vary it in any desired manner.

These two examples will give an idea of some of the many applications of this modification of remote control.

THE PRESSURE CONVERTER

A relay mechanism for converting small differences of pressure into large proportional pressures is shown diagrammatically in Fig. 54. As an illustration, assume that oil from the impeller is admitted through the pipes *J* and *H*, and the pipe *K* leads to the apparatus to be operated. The fluid entering *J* under pressure acts on the annular area of the sleeve *A*, causing it to move upward against the resistance of the

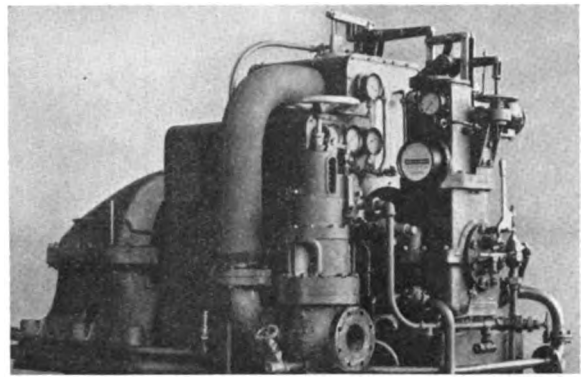

FIG. 55—AN OIL GOVERNOR CONTROLLED STEAM TURBINE

spring *S*. This brings the ports *D* and *C* into communication and admits high pressure oil into the interior of the relay sleeve *B*, causing it to move upwards against the resistance of the spring *T*, until the port *C* cuts off communication with the port *D*. A decreases of pressure in the supply pipe *J* causes the sleeve *A* to move down, cutting off communication with the port *C* until the sleeve *B* has moved down sufficiently to again register the port *C*, with the port *D*, sufficient to maintain the required pressure under the relay sleeve *B*. The exhaust from the interior of the relay sleeve *B* is through the ports *E* and *F* and the pipe *I*.

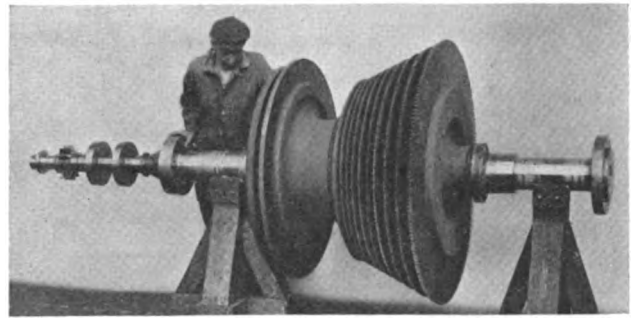

FIG. 56—THE SPINDLE FOR A 3000 KW, 3600 R.P.M. TURBINE

By proper proportioning of the annular area of the sleeve, *A*, the relay valve sleeve *B* and the springs *S* and *T*, it is possible to get any ratio of pressure conversion between the variation of pressure of the fluid supplied through the pipe *J* and the fluid taken off through the pipe *K*. Thus, for example, the normal pressure supplied to the pipe *J* may be 100 lb. per square inch, and the strength and scale of the spring *S* such that an increase of one pound of pressure will cause the sleeve *A* to move upward ⅛ inch. The scale

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and tension of the spring $T$ may be made such that 100 lb. pressure are required inside of the relay sleeve $B$ in order to stretch the spring $T$ ⅛ inch, that is, to cause the ports $D$ and $C$ to cut off communication with each other. In other words, a variation of one pound pressure in the regulating supply line $J$ will cause a variation of 100 lbs. pressure in the pipe $K$.

TABLE I

| Time P. M. | R. P. M. | Gov. Oil Pressure | Oil Temperature |
|---|---|---|---|
| 3:35 | 853 | 73.25 | 110 |
| 3:40 | 850 | 73.8 | 124 |
| 3:45 | 849 | 71.9 | 138 |
| 3:50 | 847 | 71.3 | 148 |
| 3:55 | 844 | 71.1 | 157 |
| 4:00 | 847 | 71.4 | 163 |
| 4:05 | 846 | 71.5 | 168.5 |
| 4:12 | 842 | 71.5 | 176.5 |
| 4:15 | 840 | 71.4 | 180.5 |
| 4:20 | 839 | 71.3 | 186 |
| 4:25 | 839 | 71.3 | 192 |
| 4:30 | 839 | 71.1 | 196 |
| 5:30 | 839 | 71.3 | 200 |
| | Remained at 839 R. p. m. | | |

An enormous new field of application is opened up through the application of this pressure converter, among which may be mentioned the operation of a large number of valves in series at a predetermined pressure, bleeder relay mechanism, etc.

### EFFECT OF GOVERNING SYSTEMS ON OIL

When it was first suggested to use lubricating oil in the governing system of a turbine employing a centrifugal pump, it was feared that the churning action might have an injurious effect on the oil, causing sludging and rapid deterioration of the lubricating properties.

However, the results obtained in service by the operation of about 500 turbines equipped with oil governors, indicate no deterioration or sludging of the oil but, probably due to the continual de-aeration of the oil, the oil apparently sludges less and keeps in good condition longer than where used in the ordinary lubricating systems. Furthermore, in from one to four years' operation of the turbines referred to, no case of gumming of the oil relay mechanism or failure to operate has been reported, nor have any cases of failure of the ejector and lubricating system occurred.

### GOVERNOR PERFORMANCE

The general performance of the oil governors in service has been remarkably good. The speed adjustment has remained constant, and in many plants in which they have been put into operation in parallel with other turbines, a general improvement of the regulation of the whole system has been reported. The reason for this is the remarkable rapidity with which these governors, in the smaller sizes, act combined with practically dead-beat operation, a sudden movement of the valves not being accompanied by a succession of oscillations, as is usual with the ordinary flyball type of governor not equipped with a dash pot.

TABLE II

| Time P. M. | R. P. M. | Gov. Oil Pressure | Oil Temperature |
|---|---|---|---|
| 11:35 A.M. | 810 | 72.5 | 82 |
| 11:45 | 808 | | 118 |
| | 808 | | 130 |
| 1:03 P.M. | 810 | | 200 |
| 1:08 | 811 | 70.8 | 202 |
| | Remained at 810-811 R. p. m. | | |

These governors have shown stable operation with as little as 1.5 percent speed variation between no load and maximum load, though for other reasons they are usually adjusted for 2.5 to 4 percent speed variation. They are, furthermore, remarkably uniform in performance. The relay mechanism is assembled complete, and adjusted and put on the turbine without being tested under oil pressure, and it rarely happens that any adjustment has to be made to the governor on the test floor when it is put into operation. No adjustment has had to be made to the governor other than changing the spring tension in order to obtain the correct speed and in many cases it has not even been necessary to do that much. This would be impossible with the flyball type of governor and the usual oil relay governing mechanism.

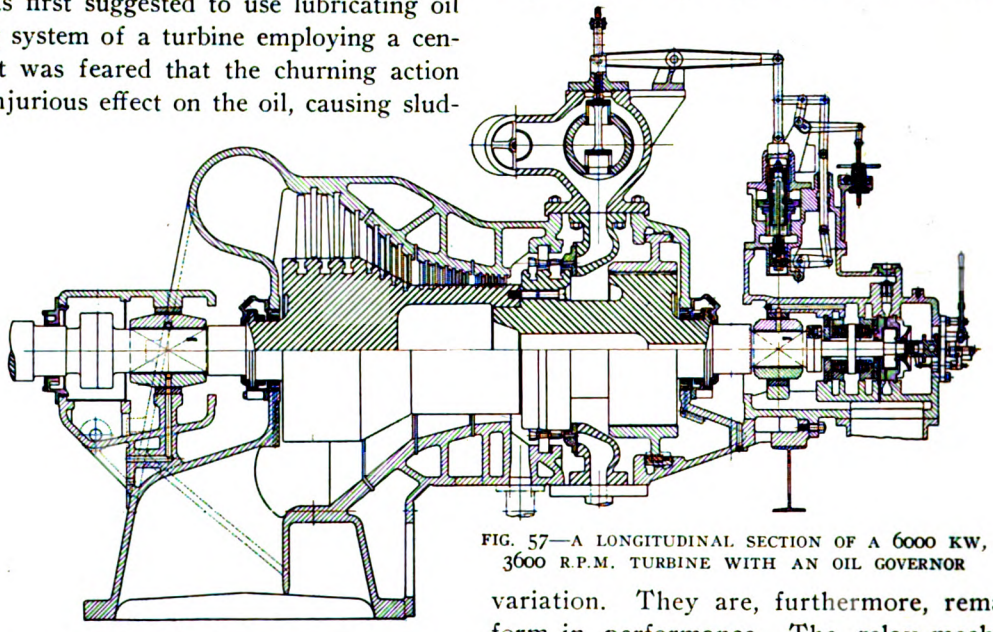

FIG. 57—A LONGITUDINAL SECTION OF A 6000 KW, 3600 R.P.M. TURBINE WITH AN OIL GOVERNOR

On the small and medium size units, the overspeeding on throwing off maximum load by tripping the circuit breaker is from 1.5 to 2 percent momentary

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increase of speed above normal no-load speed, and when maximum load is thrown on the momentary decrease in speed below maximum load speed varies from one-half to one percent.

Tables I and II show the performances of two high-speed oil governor impellers with change of oil temperature. These are different impellers, having different air separating capacities; that in Table I having somewhat greater air separating ability than that in Table II. The impeller in Table I has inlet guide vanes and the impeller in Table II is equipped with a volute inlet chamber. During both these tests, the oil cooler was out of service until a temperature of approximately 200 degrees F. was reached, after which the oil cooler was turned on sufficiently to maintain the temperature approximately constant. In the case of the impeller in Table I, the speed fell quite rapidly at first due to the increase in density, because of the elimination of air which was in the oil in its normal condition in the oil reservoir. The speed, therefore, decreased steadily from the starting speed of 853 until a speed of 839 was reached, after which it remained constant throughout the remainder of the run. Probably the reason for the continued slight decrease in speed with increase of temperature is due to the fact that the air separates more readily from the oil as its temperature increases and its viscosity decreases.

During these tests, the turbine was operated at no load, so that the governor valve opening and the position of the oil relay mechanism remained approximately fixed. Therefore, if the elasticity of the spring had not changed with increase of temperature, the governor oil pressure would have remained constant. Consequently, the change of oil pressure shown is a direct measure of the change of modulus of elasticity of the governor spring due to change of temperature, and indicates the amount of compensation for decrease of oil density which is obtained from the decreased scale of the governor spring. The oil pressure gauge had been calibrated, but the readings in Tables I and II do not agree, as a greater change of pressure is indicated in Table I than in Table II, although the change of temperature was less. The governor relay mechanism and spring were the same in both cases, so the discrepancy must be due either to gage errors not indicated by the calibration or to errors of observation.

The impeller of which Table II gives the test data was made out of the solid by drilling radial holes. This impeller showed very nearly constant speed independent of the oil temperature, though at first there was a slight decrease in speed, followed by a slight increase, after which the speed remained constant for the two or three hours that the test was continued, during which, however, no further readings except speed were taken.

# Methods of Testing Electrical Apparatus

## XV—Transformers

WHEN a transformer is connected to a source of alternating current, an energy loss takes place in the core of the transformer. This loss, known as the core loss, is composed of the hysteresis loss, due to the cyclic reversals of magnetism in the core; and the eddy current loss, due to currents sent up in the iron by the varying magnetic flux.

The core loss in a transformer is a function of the voltage, wave shape of the e.m.f. and the frequency. Guarantees are usually based on normal rated voltage of sine wave shape and at normal frequency. The standard conditions as to wave shape are difficult to obtain in practice. However, with any wave shape, there is a certain definite voltage which, when applied to a transformer winding, will produce a core loss equal to that produced by a sine wave of normal rated voltage. This equivalent voltage is determined by an instrument called the core-loss voltmeter.

The principle of this instrument is based on a comparison of the losses in a laminated core of silicon steel when excited, first, from a circuit having a sine wave, second, from the circuit whose use is contemplated. If these losses are unlike for the same r.m.s. voltage, it is obvious that the wave form of the proposed circuit deviates from that of the sine. By adjusting the voltage of the proposed circuit until the loss in the core is the same as when excited from a circuit having a true sine wave, the correction necessary to put the proposed circuit on a sine wave basis is indicated. The laminated core mentioned may be a separate unit, or it may be conveniently assembled in the same case with standard wattmeter parts to form a self contained instrument. The core loss voltmeter is made in this manner. The winding used to excite the core is in series with the stationary coils of the wattmeter movement. The instrument is in effect not a voltmeter, but a wattmeter which measures the energy consumed in its own core. In this instrument two scales are provided, one marked volts and the other watts. This obviates the use of a calibration chart for converting watts loss in the meter into equivalent sine-wave voltage.

The instrument is calibrated for the particular frequency on which it is to be used in parallel with a standard root-mean-square voltmeter on a circuit having a sine wave. The volt scale of the core loss voltmeter is carefully marked to agree with the standard r.m.s. meter and the watt scale to show the corre-

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sponding loss in the core and windings of the meter itself.

In practice the core-loss voltmeter is connected across the terminals of the transformer under test in the same manner as an ordinary voltmeter. The voltage of the circuit may then be adjusted by any convenient means until the core-loss voltmeter indicates the normal voltage of the transformer under test. The loss in the core and windings of the meter itself is then the same as it would be with a sine wave of that voltage and frequency. Likewise, the loss in the transformer under test is that which would result from the application of a true sine wave of normal voltage.

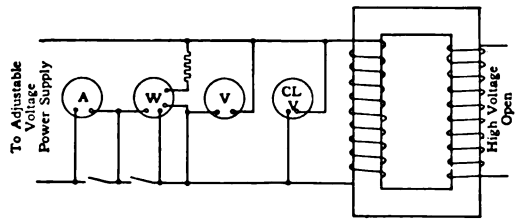


FIG. 115—CONNECTIONS FOR MAKING TRANSFORMER CORE LOSS TEST WHEN INSTRUMENT TRANSFORMERS ARE UNNECESSARY

An r.m.s. voltmeter connected in parallel with the core-loss voltmeter may not indicate the same voltage. When used on a peaked voltage wave, the r.m.s. voltmeter will indicate a higher value than the core-loss voltmeter, and when used on a flat voltage wave the r.m.s. voltmeter will indicate a lower value than the core loss voltmeter.

The voltage employed to measure the core loss may be impressed upon either the low-voltage or high-voltage winding, or a portion of the winding, care being taken that the voltage is normal for the winding or portion of the winding used. As a rule, the core loss should be measured on the total low-voltage winding. However, in some cases transformers are designed with a number of coils in the low-voltage winding for series or multiple operation, and in such cases, if the voltage of all of the coils connected in series is too high to be conveniently measured, the core loss should be measured with all coils connected in multiple rather than upon one coil of the group. If, in any case it is found necessary to measure the core loss on a portion of the winding, either in series or parallel, not less than 25 percent of the winding should be used.

The current necessary to supply the core loss and magnetization is known as the exciting current and is made of two components: the core-loss component in phase with the voltage and the magnetizing component in quadrature. The core-loss component is found by dividing the core loss by the voltage at which it is measured. The magnetizing component equals

$$\sqrt{(\text{Exciting current})^2 - (\text{core loss component})^2}$$

The exciting current of moderate and large size transformers, at rated voltage and frequency, generally varies from three to ten percent of normal rated load current. The volt-amperes excitation, i.e., apparent watts core loss, is the product of the exciting current and voltage employed in making the test. It may be assumed that the core loss value will not exceed one percent of the given kv-a rating of the transformer.

### THE CORE LOSS AND EXCITING CURRENT TEST PROCEDURE

The proper ranges and sizes of meters required may be approximately determined by the calculated values of core loss and exciting current. If the voltage and current values are beyond the range of the available meters, the required instrument transformers must be selected*. In most cases of core loss test, the power-factor of the circuit is very low, generally between 10 and 30 percent, consequently, small scale readings of the wattmeter and large multiplying factors are liable to result. This should be given careful consideration when selecting a wattmeter and also when making scale observations, as one division of the scale reading may represent several percent of the watts being measured.

The meters should be connected in the testing circuit according to the diagram shown in Fig. 115 or 116. Note in particular that the external resistance in the wattmeter potential circuit is connected to the opposite side of the circuit from that in which the current coil is connected. If the resistance is connected to the same side as the current coils, the insulation between the potential and current coil is subjected to fuil line voltage which might be sufficient to cause a breakdown.

The testing circuit should now be connected to a multi-tap testing transformer or to a current source whose voltage is readily adjustable. See that all switch or plug connections are set to give a low voltage. Be sure that everything around the apparatus is clear and safe, then close the switch which connects the multi-tap testing transformer to a power circuit of the proper frequency, thereby applying a low-voltage to the transformer on test. Before increasing the voltage to normal, open the switch which short-circuits the ammeter

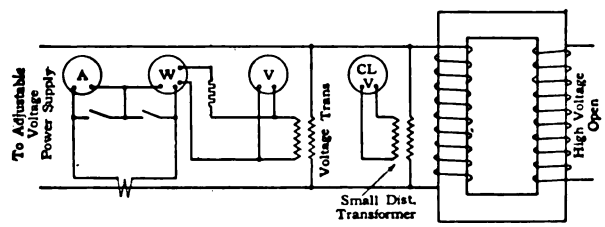


FIG. 116—CONNECTIONS FOR MAKING TRANSFORMER CORE LOSS TEST WHEN INSTRUMENT TRANSFORMERS ARE NECESSARY

and observe the value of exciting current. If it is commensurate with the applied voltage and the size of the transformer on test, close the ammeter switch and increase the voltage until the core-loss voltmeter indicates the normal voltage of the transformer. It is necessary to keep the frequency of the supply voltage as near the normal value as possible, and if the frequency is not known to be correct, it should be checked by a suitable frequency meter. Read and record the volt-

*See the JOURNAL for Mar. 1925, p. 137.

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age indicated by the r.m.s. voltmeter. Disconnect both voltmeters and the voltage transformers, if used, from the testing circuit and then read the exciting current value. Check the r.m.s. voltage of the circuit and then take the wattmeter reading. It is not necessary to reconnect the core loss voltmeter. Immediately after all readings are taken, disconnect the testing circuit from the power source.

All meter readings should be recorded, as well as the ratios of the voltage and current transformers, the wattmeter constant and the total resistance value of the wattmeter potential circuit. The volt-amperes (apparent watts) are the product of the applied voltage indicated by the core-loss voltmeter and the observed value of the exciting current.

When the scheme of connections employed is like that shown in Fig. 115, the wattmeter will indicate the core loss of the transformer under test, a very small copper loss due to the exciting current, and also the loss of its own potential circuit. If the scheme is like that shown in Fig. 116, the core loss of the instrument transformer also will be included. The copper loss, due to the exciting current, usually is negligible and is given no consideration, but the losses due to the potential circuit of the wattmeter and the voltage transformer must be determined and the sum of the two subtracted from the total loss indicated by the wattmeter, in order to get the true loss of the transformer.

The loss in the potential circuit of the wattmeter, expressed in watts, equals $E^2/R$, $E$ being the applied r.m.s. voltage and $R$ the resistance of the circuit. This correction applies when the scheme shown in Fig. 115 is used. If the scheme in Fig. 116 is used, the correction may be determined by observing the wattmeter reading when the instruments are connected for the test, but with the transformer under test disconnected from the circuit, or the correction may be found by computing the copper loss of the wattmeter potential

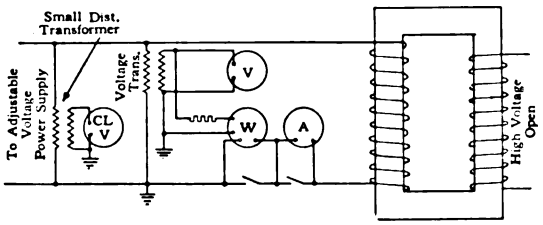


FIG. 117—CONNECTIONS FOR CORE LOSS MEASUREMENT WHEN TRANSFORMER LOW VOLTAGE IS MORE THAN 6600 VOLTS

circuit and adding to it the predetermined core loss of the voltage transformer.

When measuring the core loss of a transformer, whose rated low voltage exceeds 6600 volts, the scheme of connections shown in Fig. 117 may be used. In this scheme, it usually is unnecessary to make any correction for instrument losses, the exciting current value generally being such as to render the $I^2R$ losses in the current coils of the instruments practically negligible. When this method is employed, all meters may be read simultaneously. In Fig. 117, that part of the circuit in which the meters are connected is grounded. This makes it safe for the person making the test, provided the ground connection is properly made, and no attempt is made to change meter connections when power is on the circuit. However, this scheme must not be used when it is possible to use the method shown in either Fig. 115 or 116.

If a case arises in which the measured core loss appears to be extremely high, the trouble may be due to a local high-resistance short-circuit in the windings or, if the transformer is of the core type the trouble may be due to faulty construction of the core. In such

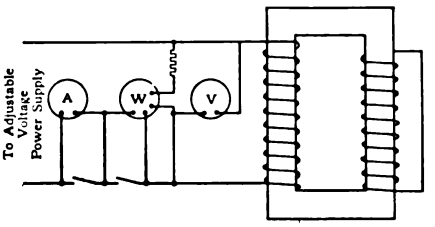


FIG. 118—CONNECTIONS FOR MAKING TRANSFORMER COPPER LOSS AND IMPEDANCE TEST, INSTRUMENT TRANSFORMERS UNNECESSARY

a case, the transformer should be operated out of oil at reduced voltage and the core and windings inspected for hot spots.

### COPPER LOSS AND IMPEDANCE VOLTAGE

The copper loss of a transformer includes the $I^2R$ losses and the stray load losses. When the rated current and resistance values of the high-voltage and low-voltage windings are known, the $I^2R$ losses may be readily computed as follows: Let $I_1$ and $I_2$ be the respective current values of the high-voltage and low-voltage windings, and $R_1$ and $R_2$ be the respective resistance values.

Then $I_1^2 R_1 + I_2^2 R_2 =$ the total $I^2R$ losses. The stray load losses are due to eddy currents and equivalent circulating currents in parallel connected windings, when not similarly disposed to each other. The proportion of stray load loss to the total copper loss may range from 0 to 30 percent, depending principally upon the characteristics of the transformer relative to the reactance and current values; high reactance and large current values being conducive to stray load loss.

The actual copper loss is determined by wattmeter measurement. The method employed is to short-circuit one winding, preferably the low-voltage, and apply to the other winding a voltage at rated frequency sufficient to produce rated load current in the windings. A wattmeter, properly connected in the circuit, will indicate the total $I^2R$ and stray load losses that occur under load conditions.

If the copper loss, measured by wattmeter at rated frequency, exceeds the computed $I^2R$ losses by ten percent, an additional measurement should be made, using decreased frequency. If other things are equal, the $I^2R$ loss will not change, but the stray load loss, which is a function of the frequency, should decrease. Hence, the measured loss will decrease in value, but

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it should not be less than the computed $I^2R$ at corresponding temperature.

### IMPEDANCE VOLTAGE

The applied voltage necessary to produce rated current in the windings of a transformer when one winding is short-circuited, is designated as the impedance voltage or impedance drop. The impedance drop is generally expressed in percent of the rated voltage, at a definite temperature. The percent impedance drop is the ratio of the impedance voltage at 75 degrees C. to the rated terminal voltage, expressed in percent. Its usual range is from 3 to 10 percent in power transformers.

The impedance drop is composed of two components, the resistance drop in phase with the current and the reactance drop in quadrature with the current. Thus, let

$E$ = the impedance drop in volts.
$I$ = the rated current in amperes of the winding to which the voltage is applied.
$W$ = the total watts input to the transformer with one winding short-circuited and with voltage and current values of $E$ and $I$, respectively, in the other.
$Z$ = the transformer impedance in ohms.
$R = W/I^2$ the effective resistance in ohms.
$X$ = the effective reactance in ohms.

Then $Z = \sqrt{R^2 + X^2}$ and $E = IZ$

The reactance $X$ is a function of the frequency of the supply voltage and leakage flux. Each winding produces leakage flux, and its amount depends upon how thoroughly the windings are subdivided and interleaved.

In general practice, the reactance of shell type transformers is kept at a low value by dividing the winding into thin flat coils and assembling them in groups as L-HH-L, L-HH-LL-HH-L, etc., where L and H represent low and high-voltage coils, respectively. The former grouping is known as 2 H-L and the latter as 4 H-L. If other things are equal, a transformer with the latter grouping will have less reactance, and hence less impedance than one with the former. In some cases, high reactance grouping is used for the inherent protection of the transformer against short-circuit stresses. A similar grouping may be used in transformers designed for operation in connection with synchronous converters to secure compounding of the direct-current voltage.

### PROCEDURE FOR COPPER LOSS AND IMPEDANCE TEST

It is important that the copper loss and impedance tests should be carefully conducted for the following reasons:—

1—The copper loss enters directly into the computation of efficiency and is also a factor in determining the true effective resistance.

2—The impedance governs the division of the load between two or more transformers when connected for parallel operation and is also used in computing regulation.

The transformer windings should be connected for normal operation. The wire or cable used to short-circuit the terminals must be of ample capacity, and as short as possible in order to carry the current without causing appreciable loss. All bolts, nuts, screws and connectors, which are included in the electrical circuit should be not only tight, but making good contact as well. Determine the temperature of the windings in a manner similar to that described under resistance tests. The temperature readings should be taken immediately following the meter readings.

Connect the meters in the testing circuit, as shown in Fig. 118. If voltage or current transformers are required, make the connections as shown in Fig. 119. Connect the testing circuit to an adjustable voltage source, taking care to make all switch and plug connections such as will give a comparatively low value of voltage. Then close the switches which connect the transformer being tested to the power circuit of the proper frequency. If the current and voltage values are commensurate with the calculated impedance voltage at rated load, increase the applied voltage until the ammeter indicates the rated load current of the winding. The impedance voltage should now be measured at the terminals of the transformer. After having read and recorded the impedance voltage, disconnect the

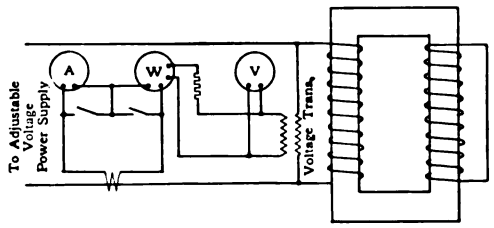


FIG. 119—CONNECTIONS FOR MAKING TRANSFORMER COPPER LOSS AND IMPEDANCE TEST, INSTRUMENT TRANSFORMERS NECESSARY

voltmeter and then observe and record the wattmeter reading. The wattmeter potential leads should be connected to the points where the voltmeter leads were connected when measuring the impedance voltage.

When the scheme of connections shown in Fig 118 is used, the wattmeter will indicate the total copper loss, i.e., $I^2R$ plus stray load losses, of the transformer, and also the watts in the potential circuit of the wattmeter. Correction for loss in the potential circuit of the wattmeter should be made in the same manner as previously described. When the instruments are connected, as shown in Fig. 119, the correction should be determined in the manner described for Fig. 117.

### SPECIAL IMPEDANCE TESTS

Transformers provided with taps for starting synchronous converters, synchronous motors, etc., have impedance tests made on the different starting taps, as follows: Short-circuit consecutively each starting tap with the common end of the winding of which it is a part, and in each case apply normal rated current to the opposite winding. Record the amperes, volts and the respective connections.

Transformers provided with taps for three-phase tc two-phase operation must have additional single-

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phase impedance and copper loss measurements made, as follows: 1—Circulate 115.5 percent of the rated single-phase current of one unit through 86.7 percent of the winding on the three-phase side; the opposite windings being short-circuited as for the regular impedance test. Record the amperes, volts and watts. 2—Remove the short-circuit from the winding which was short-circuited in test 1, then connect together both end terminals of the winding on the three-phase side, using these terminals as one line terminal and the 50 percent tap as the other. With this scheme of connections, circulate the same current in the 50 percent lead, i.e., 115.5 percent of rated single-phase current, as was circulated through 86.7 percent of the winding in test 1. Record the amperes, volts and watts.

When two transformers are connected together for three-phase to two-phase operation, the unit in which 86.7 percent of the winding is used is designated as the teaser and the other is known as the main. Test 1 is a measurement of the impedance of the teaser transformer. Test 2, is a measurement of the impedance of that portion of the main transformer, which operates in conjunction with the teaser in the three-phase to two-phase connection. The respective values of $IR$ and $IX$ obtained from test 1 and test 2, therefore, must be combined in order to determine the regulation of the teaser transformer.

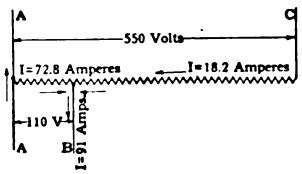


FIG. 120—SCHEMATIC DIAGRAM OF AN AUTOTRANSFORMER

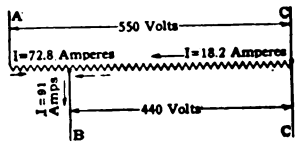


FIG. 121—THE AUTOTRANSFORMER OF FIG. 120, PRIMARY AND SECONDARY REVERSED

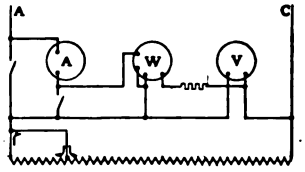


FIG. 122—CONNECTIONS FOR COPPER LOSS AND IMPEDANCE TEST OF AN AUTOTRANSFORMER

## IMPEDANCE OF AUTOTRANSFORMERS

An autotransformer is generally understood to be a transformer having a single winding which must perform the functions of both the primary and secondary elements of a two-winding transformer. In many respects it is similar to a two winding transformer, but is so connected that part of the load current is supplied by the primary current and part is supplied by the secondary current. The relative amount of current supplied by each will depend upon the ratio of transformation. If the ratio of transformation is large, the current in the secondary will be large compared with that in the primary and the proportion of load current contributed by the primary current will be small; conversely, if the ratio of transformation is small, the primary current will be large compared with the secondary current and, therefore, the primary current will supply the greater portion of the load. Since the load current is supplied from the primary and secondary in inverse proportion to the ratio of the respective number of turns in their windings, it follows that the lower the ratio of transformation, the smaller will be the transformer required for a given output; furthermore, the efficiency will be higher and the regulation will be improved.

In the development of a winding of an autotransformer shown in Fig. 120, $A$ to $C$ represents the entire winding, which generally is connected to the source of power. $A$ to $B$ represents that part of the winding which would be connected to the load and is designated the secondary; therefore, $B$ to $C$ is the primary winding. Fig. 121 shows the same development as Fig. 120, except that leads $B$ and $C$, instead of $A$ and $B$ are used as the secondary; consequently, $A$ to $B$ is the primary winding.

Assume that Fig. 120 represents a 10 kv-a transformer having a voltage rating and ratio of transformation of 550 to 110 volts, and that Fig. 121 represents the same transformer, except that the ratio of transformation is 550 to 440 volts. It is obvious that the voltage and current ratings of the respective parts of the winding are the same in each figure, yet the kv-a rating is increased from 10 kv-a in Fig. 120 to 40 kv-a in Fig. 121. Reconnecting this transformer to have it function as a two-winding transformer would give a voltage rating and ratio of transformation of 440 to 110 volts and the kv-a rating would be reduced to 10 kv-a. Since the voltage and current ratings of the respective parts of the windings are the same in each case, it is obvious that the losses remain the same. However, the percent loss and the percent impedance varies in inverse proportion to the respective ratings.

The copper loss and impedance test is most conveniently made by short-circuiting a section of the winding, as in Fig. 122, preferably that part having the greater current rating, and applying sufficient voltage at rated frequency to the remainder of the winding to produce rated current in each section of the winding. This is equivalent to regarding the autotransformer as a two-winding unit, therefore, the measured impedance is on the same basis. If $Z_t$ is the percent impedance as a transformer, and $Z_a$ the percent impedance as an autotransformer, then

$$Z_a = Z_t\ (R\text{-}1)/R$$

A simple way of determining the percent impedance drop from the test results, regardless of the scheme of connections used when making the test, is by dividing the volt-amperes taken on short-circuit by the rated volt-amperes of the autotransformer, and expressing the result in percent.

*(To be Continued)*

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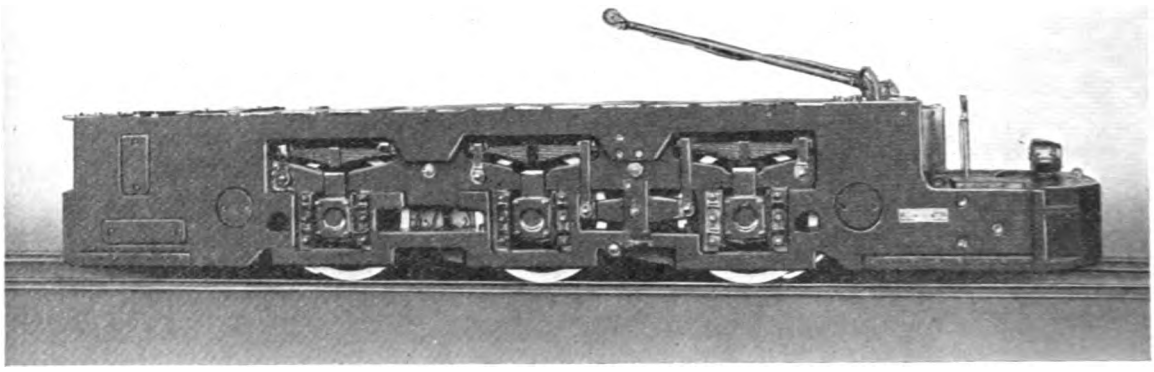
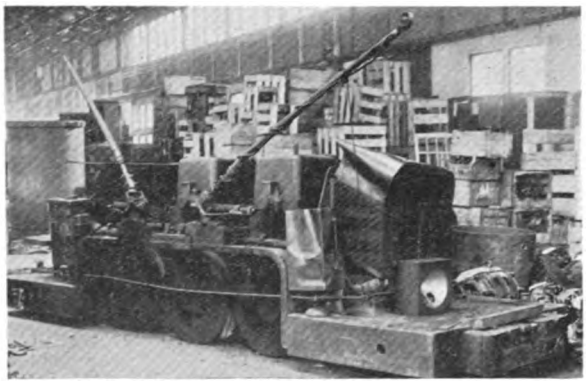
# Largest Underground Haulage Locomotive

AT the Mining Show last year the most powerful mining locomotive then built was displayed. It weighed 20 tons and was rated 300 hp. At the Mining Show this year another record mining locomotive was shown, this one weighing 38 tons and rated at 399 hp. It was one of two three-axle locomotives built for the Berwind-White Coal Mining Company. The height of the locomotives exclusive of the trolley is 46 inches.



THE LARGEST MODERN MINING LOCOMOTIVE



ONE OF THE EARLIEST MINING LOCOMOTIVES BUILT

This locomotive was built about 1896 and was retired from service seventeen years later still in running condition but considerably out of date. It had two 100 hp, 500 volt motors and weighed 43 550 pounds.

In service, these locomotives have a four-mile haul against an average grade of 2.37 percent. The maximum grade on this haul is 5.6 percent for a distance of 1000 feet. The average weight of loaded coal car is 6768 pounds and of rock cars, 8018 pounds. The average weight per car for all cars is 6905 pounds, or 3.45 tons. With this average car weight and a car rolling friction of 10 pounds per ton, one locomotive will haul from 50 to 60 cars per trip. The locomotives have sufficient capacity to haul 60 cars per trip, and make 9 round trips in 8-½ hours.

When hauling a 50-car trip the speed up the average grade is 9.4 m.p.h. On the maximum grade the speed is 7.4 m.p.h. On level tangent track, with 33-1/3 percent adhesion, the drawbar pull is 23,333 pounds at 7.4 m.p.h. The motors used on this locomotive are the largest that have ever been applied to a three-axle locomotive.

The motors embody the most improved features, having over-size roller armature bearings, through-bolts in the axl caps and motor frames, inner and outer oil seal in the bearing housings, an improved type of oil thrower and spring supported field coils. The gear case has two-point suspension with through bolts. The 6-inch axles are the largest ever used on three-axle locomotives.

Three-point equalization is provided by the same principle which locomotive builders use on large railroad locomotives. By this scheme the weight is distributed equally on the three axles under all track conditions.

An equalizer bar located on each side of the locomotive between two pairs of wheels provides side equalization. Cross equalization is obtained by a bar placed transversely on the locomotive at the third pair of wheels. This latter pair of wheels is equalized independently of the other two, providing the desired three-point suspension of the spring borne parts of the locomotive.

The control is of the semi-magnetic type. All reversing is taken care of by a manually operated reverser drum which is included in the main controller. The series-parallel arrangement of the control permits a large starting tractive effort with a low current demand.

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# Reactive Volt-Ampere Meters Should Be Used With Converters

WHEN the needle of the power-factor meter hovers so close to unity that the difference can be estimated only in tenths of a percent, almost any substation operator would be satisfied. But if a glance at a reactive kv-a meter showed a reactive load of a dozen percent or more, any good operator would do considerable manipulating of the field rheostat before considering the power-factor of his station o.k. However, the two conditions might be the same. For example, when a power-factor meter reads 99.4 percent, a reactive kv-a meter reads 11.0 percent. This is because at small angles the cosine, i.e., the power-factor, changes slowly, while the sine of the angle which is the reactive power-factor, changes quite rapidly. Small angles, therefore, are much easier evaluated from a meter which reads sine of the angle than from one which reads cosine of the angle. It is evident that to keep the reactive load to a negligible amount, a reactive volt-ampere meter should be used in conjunction with or in place of a power-factor meter.

# How to Disconnect Induction Regulators

THE primary or magnetizing circuit of an induction regulater should never be opened while current is flowing in the secondary winding. If this is done a high voltage will be induced in the primary which may be sufficient to damage the insulation or be hazardous to life.

Opening the primary of an induction regulator is like opening the secondary of a current transformer. Normally, the flux in the regulator produced by the series current flowing through the secondary winding is almost balanced by an opposing flux produced by the current flowing in the primary just as in a direct-current motor the line voltage is almost neutralized by the induced or counter e.m.f. However, if the primary is open, no current can flow in it to balance the flux from the series winding. As the voltage induced in one winding from another is in proportion to the number of turns and as the primary has many more turns than the secondary, the voltage induced in it may be dangerously large. Therefore, the line switch or circuit-breaker that connects the regulator to the source of power should, if possible, be opened before making any changes in the regulator connection.

When a polyphase regulator must be removed from the line without interrupting the service, arrangements should be made for connecting a spare regulator in parallel with the regulator to be removed before the latter is taken off the line. The rotors of both regulators should be turned to the same angular position before they are connected in parallel.

A single-phase regulator may be disconnected without interrupting the service by proceeding as follows:—

1—Turn the regulator to the mid or zero position. Open the control circuit switch so that the regulator can not be operated.

2—Place a jumper across the series leads, thus short-circuiting the series windings.

3—Open the primary and then entirely disconnect the regulator.

A single-phase regulator can thus be disconnected without disturbing the line, but it is strongly recommended that, if possible, the power can be taken off the regulator before making any changes in the connections. If the single-phase regulator is not turned to the mid position when disconnecting without interrupting the service, a high current may be induced in the windings which might be hazardous to the operator when short-circuiting the series windings.

# One Cause of Motor Current Unbalance

C. W. KINCAID

WHEN a motor is found which is taking more current in one terminal than in another, the motor is sometimes thought to be defective. In most cases, however, the motor is all right and the trouble is due to the small difference in the voltages applied to the different phases of the motor.

Suppose that while a two-phase motor is running, that one phase circuit is opened. The motor will continue to run as a single phase motor and will produce a voltage at the terminals of the open phase. This voltage will be less than the voltage on the other phase by an amount which depends on the design of the motor. Since the same magnetic flux cuts both phases of the winding, the same counter e.m.f. is necessarily generated in each phase. This being the case, the current which flows in each circuit is equal to the difference between the counter e.m.f. of the winding and the voltage applied to it, divided by the impedance of the winding. In an ordinary motor, the counter e.m.f. is only about three percent less than the line voltage. If the voltage of one phase should be more than three percent less than that of the other phase or less than the counter e.m.f. of the winding, current would flow in the direction of the generated voltage and that phase would act as a generator. In this case, the phase on which full voltage was impressed would carry the entire load of the motor plus the power fed back into the line by the phase on which low voltage was impressed.

Of course, the case just described is an extreme condition, but when this may be caused by a variation in voltages as small as three percent, it can readily be seen that much smaller variations in the voltages of different phases will cause badly unbalanced loads. For example, it was found that a 125 hp, two-phase, 25 cycles, 200 volt, 2 pole, squirrel cage motor, direct connected to a centrifugal pump, was running hot. Current readings showed for phase *A*, 225 volts and 248 amperes and for phase *B*, 226 volts, and 300 amperes. Normal full load current should be 260 amperes.

The current which flows in a winding is not proportional to the voltage impressed upon it, but to the difference between the impressed voltage and the counter e.m.f. of the winding, which may be very small so that a difference of one volt in the two phases may be a considerable percentage of that difference and, hence, a considerable difference in percentage in the currents which will flow in the two phases.

# A Spring Story

A LITTLE meter spring has told the story of its life history, and Mr. F. S. Stickney, Meter Engineer, has recorded it.

"I was born in the State of Connecticut. My early youth was spent in the form of fine drawn wire approximately ten thousandths of an inch in diameter. My pedigree is a long one, as engineers worked for many years to determine my composition. I am made from the purest of materials by the most up-to-date metallurgical methods.

At an early age I was shipped to the factory where I was rolled until I was about two thousandths of an inch thick. I was next coiled inside a metal drum and given a heat treatment, which gave me a permanent spiral shape. I was then taken to the plating room and given a beautiful finish of gold plate, which will forever protect me against the corrosive effects of the atmosphere. I was inspected for proper size and appearance, placed in an envelope, and sent over to a young lady who is the expert spring diagnostician of the factory. She has a piece of apparatus called a tension meter, and with it the strength or torque of each spring is tested.

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# 2 plants follow the same guide post

## — *to operating economy*

### In Plant No. 1
### Production up 7%
### Lubricating costs down 47%

In 1924 competitive oils for the entire lubrication of this gas manufacturer cost $2,265.

A change in lubrication was made. In 1925 Gargoyle Lubricating Oils were used throughout. Their cost was $1,201.16.

This plant's production of gas was about 7% greater in 1925 than in 1924.

It is impossible to enumerate the many ways in which savings can occur when correct Gargoyle lubricants are applied.

Some of the more tangible savings brought about by correct lubrication are as follows:—

1. Power saved.
2. Lower cost of repairs.
3. Less "time-out" for repairs.
4. Fewer shut-downs due to bearing trouble.
5. Lower labor costs to apply lubricants.
6. Lower rate of depreciation.
7. Increased production.
8. All-around plant efficiency.

### In Plant No. 2
### Temperature rise reduced 24%

This manufacturer has a steam turbine operating at 3600 r.p.m. geared to an electric generator operating at 900 r.p.m.

When a competitive oil was used the average temperature rise was 94° F.

With Gargoyle D.T.E. Oil Heavy Medium in use the average temperature rise is only 70° F.—a reduction of 25° or 24.5%.

In addition, the use of Gargoyle Oil Heavy Medium on a turboblower has reduced the temperature rise on this machine from 80° F. to 65.3° F.—a reduction of 22.3%.

(From the records of a Michigan manufacturer)
Vacuum Oil Company File No. 42227

LET us help you to locate, not only possible power savings, but easily attainable savings in repairs and labor costs.

This may be brought about by a change to the correct grade of oil or the installation of more efficient methods of applying the oil—or both.

Our 62 years of specialized study of lubrication gives a wealth of practical experience on which your engineers may draw.

We shall be glad to get in touch with you.

NOTE: On request we will send you, without obligation, our authoritative treatises: "Steam Turbine Lubrication," "Hydraulic Turbine Lubrication." Write for your copies.

# Vacuum Oil Company

*Headquarters:* 61 BROADWAY, NEW YORK

*Branches and distributing warehouses throughout the country*

GARGOYLE

## Lubricating Oils

The world's quality oils for plant lubrication




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Springs are classified according to strength, and, when used in direct-current instruments, are "paired off" to give a pair of springs of exactly the proper torque. I passed my examination on the tension meter and was found to be slightly stronger than the average. I was, therefore, paired off with a spring slightly weaker than the average. We were then assembled together in a direct-current voltmeter.

The voltmeter passed a number of inspections, was calibrated, tested, shipped and mounted on a switchboard. Nobody ever thinks of me now but I am on the job 24 hours a day and, as an engineer would say, 'My deflection is always proportional to the line voltage to which my voltmeter is connected.' I am really very proud of my job as it is the most important one inside the meter case. I am glad the people at the factory took so much trouble to get me started right in life as I am a truth-loving individual and would hate to see my friend, the pointer, telling the station operator the system voltage is 650 volts when it really is only 600. Just because I have had a chance to write my life history I don't want anybody to think I am better than other meter springs. We all get the same treatment and all are proud of our veracity."

# The JOURNAL QUESTION BOX

Our subscribers are invited to use this department as a means of securing authentic information on electrical and mechanical subjects. Questions concerning general engineering theory or practice and questions regarding apparatus or materials desired for particular needs will be answered. Specific data regarding design or redesign of individual pieces of apparatus cannot be supplied through this department.

To receive prompt attention a self-addressed, stamped envelop should accompany each query. All data necessary for a complete understanding of the problem should be furnished. A personal reply is mailed to each questioner as soon as the necessary information is available; however, as each question is answered by an expert and checked by at least two others, a reasonable length of time should be allowed before expecting a reply.

2850—The Compensator Winding on Induction Regulator—Referring to the schematic diagram of a compensator used in connection with the compensation of voltage regulators for inductive line drop, shown in Fig. (a), please explain why the coils connected between *A* and *C* are wound on an iron core, and how it is possible for current to flow through the compensator winding on the control coil. F. I. M. (PA.)

On a three-phase system two current transformers must be connected as shown to deliver to the compensator a current of the proper phase direction. This current is 1.73 times as large as that delivered on a single-phase system by a single current transformer. The three-phase compensator is wound for this increased current and an autotransformer, *C* to *A* in Fig. (a), is placed in the compensator to split up this increased current so that a standard control coil may be used. In an autotransformer as shown in Fig. (a), if the two sections are equal the currents in leads *A* and *C* must be equal regardless of whether the control coil is in circuit or is short-circuited. This is true except for the slight effort of the exciting current of the autotransformer and the coil *A* to *C* must have an iron core in order that this exciting current may be small enough to be negligible. E. E. L.

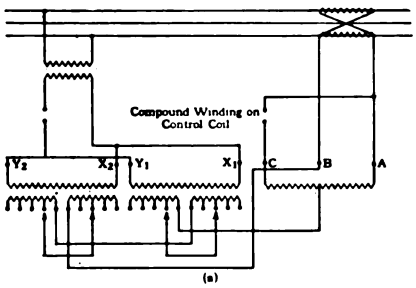


FIG. 2850

2851—Zig-Zag Transformer for Grounding—Why is it preferable to use a zig-zag instead of a star-connected transformer for the purpose of grounding a three-phase system? G. A. W. (N. Y.)

It is not always preferable to use zig-zag winding to ground a three-phase system. The purpose of the zig-zag winding is to permit the unbalanced direct current from the third wire of a three-wire circuit fed by a synchronous converter to get back into the system. The zig-zag or interconnected star winding permits this direct current to circulate through the transformer winding without changing the magnetic conditions. The magnetizing action of each of the two coils in each phase, magnetically oppose and thus cancel their magnetizing action. If it were simply a case of grounding the system, the neutral of a star bank of transformers, or the neutral of a three-phase star-connected reactance coil could be used. E. G. R.

2852—Polarity Markings of Instrument Transformers—What is the meaning of polarity markings on instrument transformers as shown in Fig. (a)? R A. B. (MASS.)

The polarity marks as shown at the left indicate that the instantaneous potential in the second is just the same as in the primary, in other words the instantaneous direction of current in the secondary is just the same as it would be if the transformer were removed and the primary and secondary wires connected together. The polarity marks shown at the right indicate, of course, exactly the opposite. C. R. R.

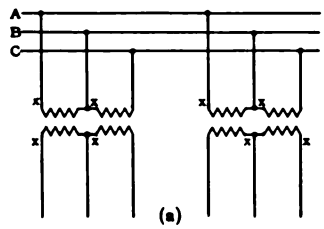


FIG. 2852

2853—Resonant Test Voltage—Please give the explanation for voltmeter reading obtained when using line voltage (2200 volts) to test winding of a 2200 volt, three-phase, 25 cycle motor for ground. Winding is known to be free of ground by other tests. Using a 100 watt, 20 to 1 ratio instrument potential transformer and a two scale 0-150 volt; 0—300 volt voltmeter. By connecting one primary lead of the potential transformer to ground and the other lead to each successively, the voltmeter reads 65 × 20 = 1300 volts which is the potential difference of power lines and ground. Upon connecting one primary lead of the potential transformer to line and the other to the winding of a 250 hp, 2200 volt motor the voltmeter reads 125 volts × 20 = 2500 volts. Lower readings are given when testing a 100 hp and 50 hp winding in the same manner. It is also noted when testing the same winding but using the other scale on voltmeter a different reading is given. J. L. J. (N. Y.)

You seem to have run into a condition of resonance. As stated in the first part of the question the voltage from any line to ground is approximately 1300. The potential transformer has a very high reactance and probably also a small capacitance between turns. The combination of windings, insulation and frame of the motor form a relatively high capacitance whose value would depend upon the design of the motor but would be greater for the larger motor. With the connections set up as shown in Fig. (a) you have established a circuit from one of the lines through the reactances of the transformer, then through the capacitance of the motor insulation to ground. An e.m.f. of 1300 volts is impressed across the whole circuit, but it is characteristic of a resonant circuit that the voltage across either the reactance or the capacitance may considerably ex-

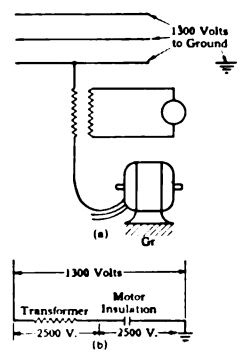


FIG. 2853

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ceed the total circuit voltage. Apparently the 50 hp motors happen to have the right capacitance to ground to establish this resonant condition. With the smaller motors, the lower capacitance would mean that the resonant frequency was somewhat different from the frequency of your circuit, hence the lower voltage which you obtained. Connecting the voltmeter on a different voltage tap would probably also upset the resonant condition slightly, giving a different reading. You should note that such a test imposes a much more severe voltage on the motor insulation than the normal 1300 volts to ground; in other words the voltage across the insulation is of the same order as that read by the voltmeter.

C. R. R.

2854—AN UNUSUAL CASE OF MAGNETISM—A piece of hard steel measuring 3/32 by 1/2 by 30 inches has in some manner become magnetized as follows:—When tested with a compass which is passed along its length it shows a number of distinct poles. The figures after the pole letters refer to the distance in inches S-0, N-4, S-8.5, N-12, S-16.5, N-19.5, S-23, N-27, S-30. I am curious to know why.

S. E. H. (CALIF.)

The finding of poles at intervals of approximately 3 to 4 inches along a piece of hard steel is not unusual, as it is possible, by the placing of suitable magnetizing coils, to accomplish this result. The Poulsen telegraphone operates on that principle and relies upon the maintenance of difference in polarities and decrease of magnetization at various points along the wire as a means of placing a sound record thereon. It is not possible to explain just how this particular steel obtained this magnetic condition, although it may have been placed in a large coil of wire which was open circuited at the time, and that through it a heavy direct current was passed.

S. M. K.

2855—EQUATIONS FOR INSTANTANEOUS VOLTAGE AND CURRENT—In the treatment of synchronous motors given by Steinmetz in his "Alternating-Current Phenomena", 5th edition, equations are developed for the counter-e.m.f. and for the current when the constants of the machine, the impressed voltage and the motor power are given. They appear on p. 318 as equations 19 and 20 respectively, and are reproduced below.

$$e_1 = e_0 \frac{z}{r}\sqrt{\frac{1}{2}\left\{\left(1-\frac{2rp}{e_0^2}\right)+\left(\frac{x}{2}\cos\phi+\frac{r}{2}\sin\phi\right)\sqrt{1-\frac{4rp}{e_0^2}}\right\}}$$

$$i_1 = \frac{e_0}{r}\sqrt{\frac{1}{2}\left\{\left(1-\frac{2rp}{e_0^2}\right)+\left(\frac{x}{2}\cos\phi-\frac{r}{2}\sin\phi\right)\sqrt{1-\frac{4rp}{e_0^2}}\right\}}$$

The $\phi$ of the equation is referred to on page 316 as an angular parameter, and again on 318 states that it has no direct physical meaning. It appears, however, quite necessary to know what it is in order to use the equations to obtain a solution. Can you give me an explanation of this and show me how to derive the value of $\phi$ when $e$, $p$, $r$ and $x$ are known? In general, how much greater are the currents that the field windings and armature windings can carry without overheating, than the currents in these circuits when the machine is delivering full load at unity power factor?

O. S. (N. Y.)

The two equations given define the generated voltage $e_1$ of the motor and the currrent ($i_1$). These two values are not independent but depend on each other for their values when a given load at a given terminal voltage ($e_0$) is being carried by the motor. In other words the current drawn from the line by a synchronous motor depends on (1) the line voltage, (2) the voltage generated in the armature by the field, called here the excitation voltage, (3) the power in the motor and (4) the synchronous impedance of the motor winding. Evidently if only three of these factors are known all that can be solved for is the relation between the current and the other unknown factor. Hence if $e_0$, $p$, $r$ and $x$, are all that is known, the best way to obtain the motor characteristics is to plot the series of curves shown on page 325 of Mr. Steinmetz's book. The use of the parameter ($\phi$) is only for convenience in calculation and it has no readily apparent physical meaning. In plotting the equations, arbitrary values are assigned to $\phi$ and substituted in the equations for $e_1$ and $i$, which can then be plotted against each other to obtain the "power hill" drawn on p. 325. Each curve here represents a given amount of power and the current required is that corresponding to the excitation voltage plotted as abscissa on the graph. Equation (7) p. 316 gives the current for any particular value of excitation voltage ($e_1$) and may be used if all factors except current are known. However, a much better understanding of the machine can be obtained by calculating the curves. General relations governing the allowable current in the motor winding are difficult to give. If a machine is designed for unity power-factor operation and is maximum rated, the current values cannot be exceeded for any length of time without increasing the temperature rise. If it is designed for 80 percent power-factor operation, operation at unity power-factor will reduce the armature current in the ratio of 10 to 8 and the field current will be reduced depending on the saturation of the field magnetic circuit and the armature reaction of the machine. One machine, picked at random, requires 75 percent of 80 percent power-factor excitation full-load for unity power-factor operation. It must be understood however, that this value is subject to wide variations depending on the design of the machine.

D. E. M.

2856—TESTING TRANSFORMER—A present single-phase, high-voltage testing set installation consists of the following apparatus connected as shown in Fig. (a). The testing transformer is

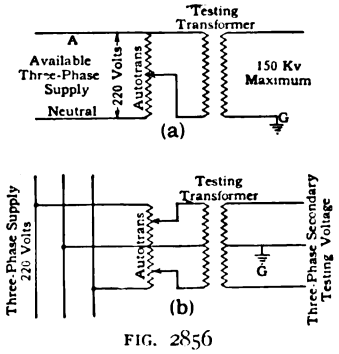


FIG. 2856

a 25 kv-a, 60 cycle, 220 volt primary, 150 kv secondary single-phase, oil-immersed, self-cooled transformer. One end of the secondary is brought through a high voltage bushing and the other end is grounded. There is a regulator panel with an autotransformer to vary voltage in one percent steps from zero to 100 percent. If possible how would connections be made to obtain three-phase with one additional transformer? What additional regulator equipment would be necessary and how would it be connected?

M. M. (LA.)

By the use of a second complete set exactly the same as the first, the two may be connected in open delta. The arrangement would then be as shown in Fig. (b).

E. G. R.

2857—REACTANCE OF WIDELY SPACED CONDUCTORS—The formula for the inductive reactance of a mile of wire is,—

$X_L = 2\pi f\,(80 + 741.1 \log_{10} D/r)\ 10^{-6}\ \Omega$'s per mile

Where $D$ = space between conductors $\frac{r}{1}$ = radius in inches of the wire; $f$ = frequency. From this formula it is evident that the inductive reactance can increase without limit since $D$ may increase without limit or nearly so. If $D$ increases the log of $D$ will increase without limit and as a result the expression increases without limit. From this it may be seen that a transmission line whose separate lines were several miles apart would have an extremely high inductive reactance. a—Am I right in my assumptions? If so is it possible to run a transmission line whose conductors are widely separated? b—If my assumptions are not true, is there a distance $D$ beyond which the formula ceases to hold good?

J. T. (OHIO)

This formula is not complete for the case at hand; also your application of the formula is not complete. Let us consider the application of the given formula first. With these equations it is doubtless true that for infinite conductor spacings, the reactance becomes infinity. However, in any formula involving infinity, the way in which the constants approach infinity is important. With such problems, in practice, we are limited to distances of a few thousand miles. If we apply the formula you give to hypothetical transmission lines of the conventional spacing and of extreme spacing, we do not find the great increase in inductance we would expect from a casual inspection. For instance, for a circuit of 00 solid conductor wire one mile long and spaced 8 feet apart, the reactance is about 1.03 ohms. If the same conductors are spaced 10 miles apart the reactance is 1.86 ohms. For a spacing of 1000 miles the reactance is 2.42 ohms. Thus there is not an inordinate increase in transmission line reactance at even extraordinary spacings. The reason for this you will see from the formula, for when a number increases very rapidly its logarithm increases but relatively little.

While generally used for the inductive reactance of a mile of wire, the equation you quote is merely an approximation which is sufficiently correct when the distance between wires is negligible compared to the length of the wire. This is the usual case, but is not the case which you have con-

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sidered. The complete equation for inductance is—

$$L = 2\,(l\,Log_\epsilon \frac{D\,(l+\sqrt{l^2+K^2})}{R\,(l+\sqrt{l^2+D^2})} - \sqrt{l^2+K^2} + \sqrt{l^2+D^2} + R - D + \tfrac{1}{4})$$

where $l$ = length cm; $D$ = separation cm; $R$ = radius of conductor cm; $L$ = inductance in centimeters; $L \times 10^{-9}$ = henrys. You will notice that where both $D$ and $R$ are negligible as compared to $l$ this equation reduces to approximately,—

$$L = 2\,l\,log_\epsilon\, D/R + \tfrac{1}{4}$$

If you will change this equation to common logarithms, $l$ to one mile and the value of inductance to henrys, it is the same as the one you have quoted.

Your question is of theoretical rather than practical interest. If, however, you wish to consider a case where the spacing between wires is comparable to the length of the wires you must use the complete equation given above or else a simplification involving the assumption that the diameter of the wire is negligible compared to either the length or spacing which will give a different approximation from the one quoted in your question.

Assuming an infinite spacing of wires, the complete expression for inductance is indeterminate. However, by differentiating to determine the limits which the indeterminate part approaches, we can get the following very close approximation to the value of the inductance when the wires are spaced at infinite distance apart:—

$$L = 2\,[l\,log_\epsilon\left(l+\frac{\sqrt{l^2+K^2}}{K}\right) - \sqrt{l^2+K^2} + K^2 + \tfrac{1}{4}]$$

which has a finite value.

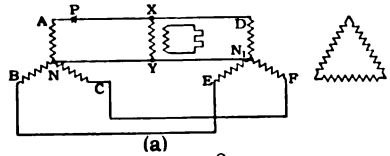
All of the above refers to solid conductors. The practical case would involve stranded conductors which give somewhat different results. Formulas taking into effect the stranding of the conductors are given in "Electrical Characteristics of Transmission Circuits" by Wm. Nesbit, Third Edition, p. 7. More complete discussions are given by Mr. H. B. Dwight in "Transmission Line Formulas" and "Constant Voltage Transmission."

C. R. R. & J. F. P.

2858—Grounding Transformer Secondary Neutral—Kindly inform me if it would be possible to ground the neutral or middle legs on secondary side of single-phase transformers (2300 volt primary, 115-230 volts secondary). There will be about five of these single-phase transformers connected to each of the three phases. The windings of the generator are not grounded. In addition to the above mentioned single-phase transformers there will be several banks of single-phase transformers connected delta-delta for three-phase 230 volts secondary. E. G. D. (N. J.)

It is common practice to ground the secondary neutral of distribution transformers. The principal reason for doing this is that it greatly decreases the hazard from fire and to life. Delta-delta banks of transformers are commonly grounded by connecting to ground the mid point of one transformer secondary. C. A. S.

2859—Three-Phase, Four-Wire and Open-Delta Loads—A three-phase, four-wire circuit supplies a star-delta bank of transformers having a balanced load as shown in Fig. (a). A single-phase load is also taken off from phase $A$ to netural at $X$-$Y$. Is it not correct that, if the impedance from $A$, $X$, $Y$, $N$ is the same as from $D$, $X$, $L$, $N_1$, the load bank will act to supply half the load $XY$ from phase $DN_1$, the balance coming from phase $AN$? If $XY$ were close to $DN_1$ the proportion supplied by $DN_1$ would be greater, and a condition arise due to $XY$ being relatively great in comparison with the phase $DN_1$ where the bank $DEF$ would be



(a)

FIG. 2859

burned out. The above supposes a connection between $Y$ and $N_1$. Could you let me have an analysis of currents supposing $XY$ were close to $DN_1$ (no impedance between) also, with a connection between $Y$ and $N_1$ and the circuit open at P. In this latter case the phase $DN_1$ will maintain the voltage across $XY$ up to its ability, I presume, by a transfer of energy through the secondary delta.

G. A. V. (CANADA)

Let us first assume that the secondary of the star-delta bank is simply supplying an isolated load and is not connected to a network. In this case it is obvious that all of the energy supplied to the single-phase load at $XY$ must come from the scource of power $AN$. Now suppose that the secondary of the star-delta transformer is connected into a secondary network, by which it may get power through the secondary circuits from the original source of power. Now let power be drawn at $XY$ to the extent that the potential at $XY$ is still greater than at $DN_1$. The star-delta bank will still draw power from the source $AN$ and will, therefore, not furnish any of the power drawn at $XY$. Now let $XY$ draw more power until the potential at $XY$ falls below that at $DN_1$. Obviously $DN_1$ will then not draw power from $AN$, but will furnish part of the power drawn by $XY$. Now the relative amount of the power furnished to $XY$ by $AN$ and $DN_1$ back through the secondary network to the original source of power, depends on the relative impedance of these two complete paths, and not on the relative impedance between $AN$ and $XY$ and between $DN_1$ and $XY$. If $XY$ is close to $DN_1$ it is not unreasonable that a condition might exist which would overload and burn out $DN_1$. If $P$ were open all of the power must come back through the secondary network and $DN_1$ would be sooner overloaded and might burn out.

E. S. R.

2860—Cable Testing—In the usual three-phase cable testing the three conductors are connected to the different phases and the sheath is grounded as shown in Fig. (a), thus stressing the insulation between conductors, and between conductors and sheath. With the connection as shown in Fig. (b), with the sheath floating, will not the same test as above be duplicated with the exception that the insulation between conductor $C$ and the sheath will not be stressed? If the voltages are unbalanced will there be an induced voltage in the sheath? M. M. (LA.)

We assume that Fig. (a) indicates the application of three-phase test voltage. There is no single-phase test which will exactly duplicate the stresses of the three-phase field in a cable. As a practical matter, however, single-phase testing is the usual method. There are two systems of testing. If the prescribed test between conductors and ground is the same as that between conductors, the usual method of testing is to apply the following two tests: Conductors $A$ and $B$ against $C$ and ground, followed by a second test of conductors $A$ and $C$ against $B$ and ground. These two tests will apply to full test voltage between all pairs of conductors and between all conductors and grounds. If the prescribed test to ground is less than the test between conductors, as is usually the case, this method cannot be used because if the full test between conductors is to be applied, the permissible test to ground will be exceeded. To do this, the connection is somewhat similar to the connection of Fig. (b). Two transformers may be used, but the usual method is to take a transformer with the midpoint available and ground the midpoint. Three tests are required. The first is a test between two conductors and the third conductor, for instance, conductors $A$ and $B$ against $C$, with the sheath connected to the grounded midpoint of the transformer. The second test is conductors $A$ and $C$, for instance, against conductor $B$. This gives the full test between conductors pair by pair. During the tests, the voltage to ground is only half of the test between conductors, and this is practically always less than desired test to ground. Therefore, with the usual

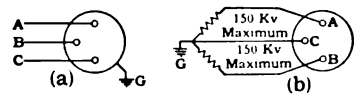



FIG. 2860

transformer connection, the preceeding two tests are followed by one single-phase test of the three conductors tested against the sheath. In no cable testing should any conductor (including the lead sheath) be left floating, and in fact, this is forbidden by the A.I.E.E. Standardization Rules. In the connection shown in Fig. (b), the correct voltage would be applied between conductors, but the voltage applied between the conductors and the sheath is indeterminate. The sheath would take on a voltage determined by the relative values of the capacity between conductors $A$ and $B$ and lead, between conductors $C$ and lead, and also the unknown capacity and the lead sheath to ground. The actual test applied by Fig. (b) is therefore indeterminate, and possibly dangerous, and it is for such reasons that the requirement is made that all conductors and the sheath should be connected at all times to some definite potential. D. M. S.

2861—High-Slip Versus High-Torque Motors—Referring to the article entitled "High-Slip Versus High-Torque Motors" in the February issue of the Journal, the summary after the first paragraph reads:—"$A$—A high-slip motor, designed with a high resistance rotor and normal reactance. $B$—A high-torque motor, designed with normal resistance and low reactance." If we alter the design of a motor so that we change

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the ratio of $X_2$ to $R_2$—being reactance and resistance per phase respectively—while keeping the total secondary impedance constant, we find that the actual maximum torque will be attained when $R_2$ equals $X_2$ and this actual value depends upon factors of design. If $R_2$ is increased further the starting torque decreases. The greater the rotor resistance the greater the slip. It is presumed that what is meant in the article referred to is a motor whose resistance has been increased past its point of maximum torque. With reference to *B* it is presumed that the small reactance is obtained by decreasing the air-gap. Will you please advise me regarding these two points and particularly the assumption made in the preceeding paragraph. E. J. K. (ILL.)

The motor referred to as "*A*—A high slip motor, designed with a high resistance rotor and normal reactance" has a value of rotor resistance which is less than the value of rotor reactance. If this motor had a value of rotor resistance, the maximum value of torque (which is shown in Fig. 1 of the article referred to) would be at start instead of at 525 r.p.m. and would be equal to the torque at 525 r.p.m. If the rotor resistance were greater than the rotor reactance, the maximum value of torque would be at start and would be less than the value shown on the curve at 525 r.p.m. With reference to "*B*—A high torque motor, designed with a normal rotor resistance and low reactance", low reactance is not obtained by decreasing the air-gap. On the contrary this would increase the reactance. The motors referred to in the article "High-Slip Versus High Torque Motors" have the same air-gap. A low reactance is obtained by reducing the product of leakage flux and the square of the number of conductors. This is accomplished by a reduction in leakage path areas or by a reduction in number of conductors or by both. F. J. J.

2862—BLACK VERSUS WHITE PAINT FOR TRANSFORMER CASES—In the case of transformers that are exposed to the open sky, would there be much, if any, difference in the temperature rise if they were painted white instead of black, which is the usual application? It comes to my mind that solar water heaters are painted black and exposed to the sun for the purpose of collecting heat. F. W. S. (CALIF.)

This is a complicated question and involves so many factors that no positive answer can be given that fits all cases. For certain types of transformers which have their principal load at night it is believed that there would be no advantage in using the white paint because the principal heat that is to be dissipated originates on the inside of the transformer from power losses supplied by the electrical line and the absorption of heat from the sun is of secondary importance. On the other hand, power transformers that have their peak load at the time they are securing a considerable amount of heat from the sun might, with advantage, be painted white insofar as the heat losses alone are concerned. On the other hand there are too many things against the employment of white paint for such a purpose from the standpoint of the appearance of the equipment which is subject to handling by greasy hands and when mounted outdoors is subject to, in many locations near large cities, the accumulation of coal soot as to make its employment questionable. For room temperature radiation, i.e. for the very long heat wave lengths, there is no great difference in efficiency between the white paint and the black paint provided these paints are of the so-called non-metallic type, i.e. paints which do not carry the pure metals, but carry oxides. There is, however, a preference favoring the white in the absorption of the shorter wave lengths such as emanate from the sun and are absorbed by the transformer tank and converted into heat and later reradiated at a longer wave length. S. M. K.

2863—POWER-FACTOR OF RECTIGON BATTERY CHARGERS—Please explain by means of vectors why rectigon battery chargers and other half and full wave rectifiers of the bulb type have such a low power-factor. Also relative difference between half and full-wave rectifiers in this respect. C. L. R. (MASS.)

Rectigon battery chargers have a comparatively low power-factor due to the fact that their transformers are designed with large leakage reactance for self regulation. In fact, the steel case of the rectigon is used as a part of the magnetic circuit, providing additional leakage. The leakage reactance increases considerably the wattless component of current and consequently decreases the power-factor of the unit. Assuming that the value of true watts at a certain period of rectification is $EI'$ and the value of the wattless component is $EI''$ and considering a half wave rectifier, the power-factor of the first half of the wave (rectified) is equal to:—

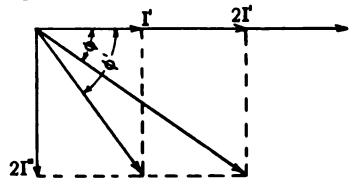

FIG. 2863

$$\frac{EI'}{\sqrt{(EI')^2+(EI'')^2}} \quad \ldots\ldots\ldots\ldots (1)$$

In the second half cycle, the value of true watts is equal to zero while the wattless component is $EI''$ as before and the average power-factor for the complete cycle is equal to:—

$$\frac{EI'}{\sqrt{(EI')^2+(2EI'')^2}} \quad \ldots\ldots\ldots\ldots (2)$$

In case of a full wave rectigon the average power-factor is equal to:—

$$\frac{2EI'}{\sqrt{(2EI')^2+(2EI'')^2}} = \frac{2EI'}{2\sqrt{(EI')^2+(EI'')^2}} = \frac{EI'}{\sqrt{(EI')^2+(EI'')^2}} \ldots (3)$$

Comparing formulas 2 and 3 it is obvious why the power-factor of a half wave rectigon is smaller than that of a full wave rectigon. By means of a vector diagram, the above can be represented, as in Fig. (a). Where $I'$ and $2I''$ are the current components of a half wave rectigon. $2I'$ and $2I''$ are the current component of a full wave rectigon. Cos $\phi$ = power-factor of a full-wave rectigon. Cos $\phi'$ = $FF$ of a half-wave rectigon. It is understood that the r.m.s. values of current and voltage are considered and that other variables as wave shape, etc., are eliminated from the above discussion. The relative difference between the half wave and full wave rectigon is in the neighborhood of 50 percent and 80 percent. S. B. K.

2864—TRANSFORMER CONNECTIONS—It has been our practice to take house lighting from power banks over the system using connections as shown in Fig. (b). In so doing quite often a mistake is made and we find that the house circuit has been taken from phase *C* and neutral ground, Fig. (b), resulting in too high a voltage. But after a change is made to either of *A* or *B* phase to neutral ground the proper voltage is obtained. Would the secondary voltage in Fig. (a) be the same from either of the three-phase to neutral ground. In Fig. (a) should voltage from either of three phases to *N-G* be the same. In Fig. (b)—Is voltage from either of three phases to *N-G* the same? Would dotted line connection make any change in secondary voltage from either of three phases to neutral ground in Fig. (b)? T. B. H. (NEW JERSEY)

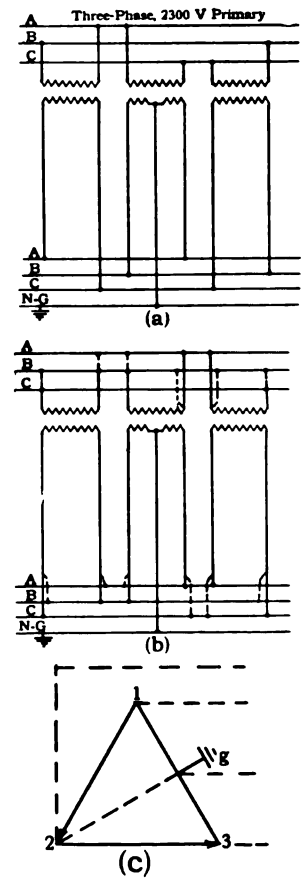

FIG. 2864

(a) If in Fig. (c) voltage $V_{1\text{-}2}$, $V_{2\text{-}3}$, $V_{3\text{-}1}$ = 100 volts
voltage $V_{2\text{-}g}$ = ½ $V_{3\text{-}1}$ = 50 volts
$V_{g\text{-}1}$ = ½ $V_{3\text{-}1}$ = 50 volts
$V_{2\text{-}g} = \sqrt{100^2 - 50^2} = 86.6$ volts

(b) The connections in Fig. (b) are correct. The connection *A* to neutral or *B* to neutral will give you 115 volts for lighting, that is, the equivalent of 230/115 volt, three-wire connection on one phase only. The connection *C* to neutral is 90 degrees out of phase with *A-B* and the voltage is 115 times the square root of 3 or 200 volts. It must be remembered that *N-G* is not the three-phase neutral. Transformer *AB* must be larger to carry the extra single-phase load. R. A. B.

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# THE ELECTRIC JOURNAL

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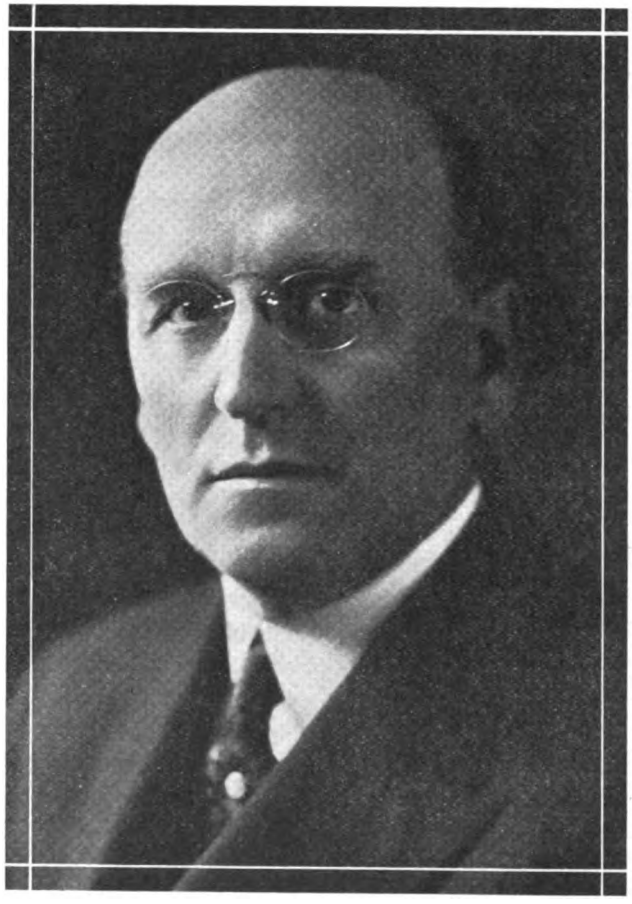
## What the A. E. R. A. Is Doing for the Industry

R. P. STEVENS
President,
American Electric Railway Association.

THERE is probably no better purpose to which can be put the space which the Editor has so kindly invited me to use in THE ELECTRIC JOURNAL than to emphasize the value of the service which the American Electric Railway Association renders to the local transportation industry and the many thousands who are in the employ of the industry.

At this time of year, when the industry's attention is focussed on the Cleveland Convention, there is an understandable feeling that the Convention is the chief feature of the Association's activity. The Convention happens to be the one spectacular incident in the Association year. It brings together men from all parts of the country to listen to addresses, to take part in discussions and to inspect the Exhibit. In connection with the Convention the officers of the Association are called on to write articles for the various publications that serve the transportation industry, and from Association headquarters there goes forth a great amount of correspondence and convention-boosting material. Nevertheless, the Convention, despite its magnitude and its importance, is but one of the activities of the Association, and not greater in value to the industry than the every-day service which the Association renders throughout the year to the membership.



R. P. STEVENS
President, Republic Railway & Light Co.

Association headquarters is the place to which any man in the industry may turn for information as to the latest and best methods and practices. Not only is it a clearing house for ideas but, through its committee activities, it is a creative organization.

The test of the value of any organization is in the service it can render a member in an emergency. Because of its up-to-dateness and the completeness of its service the American Electric Railway Association enjoys an eviable reputation for efficiency. There is no problem in connection with our business so great or small but it can be dealt with through the Association. I doubt if anyone can appreciate fully the tremendous work which the Association does for the industry, unless he has contact with it through membership on the Executive Committee. Only by close contact can one know how great has been the progress toward stabilization of the industry since the position of Managing Director was created and Lucius S. Storrs accepted the invitation of the Advisory Council to fill that position. Through many years of executive responsibility in the electric railway industry, Mr. Storrs became thoroughly familiar with the problems faced by the average executive. This knowledge, together with his great natural ability and tact, have made our Managing Director's services invaluable.

Under his direction at Association Headquarter's is a capable and loyal staff, equipped to handle any and every problem, whether it be one calling for engineering skill, one involving the salesmanship of transportation, one concerning a problem of taxation or accounting or one calling for a mass of statistics. This service is available to member companies every day in the year, on short notice. I know of no Association that returns so great value to its members for the money which membership costs, nor do I know of any Association more economically and efficiently conducted.

In recent years the industry has faced tremendous difficulties. Some of them have been all but in-

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superable. Yet we have overcome them. We have demonstrated that the electric railway industry is a permanent industry, that nothing yet has been devised to take its place in the economical handling of mass transportation. We have demonstrated the adaptability of our operating organizations to the demands of the times. We have tested out new vehicles, made tremendous improvements in the appearance and efficiency of the electric car, proved the practicability and safety of one-man operation, developed the freight-carrying end of the service, met the trials of modern operation in heavily congested streets, co-operated with communities and organizations in solving public problems, and, in general, have shown ourselves to be thoroughly alive to the needs of our business. To do this, much work has been necessary, and it has been undertaken and carried through largely by Association committees, whose members give their time and experience without pay.

And when I speak of the "Association," I mean not only the American Electric Railway Association but also its affiliated associations, those of the Accountants, the Claims men, the Engineers and the Transportation and Traffic men. The work of these affiliated associations is an integral part of the general Association activity. Upon the outcome of studies made by these Associations and their committees depends in large measure the future practice of the industry.

I sometimes wonder if all of our member companies appreciate the great benefits which accrue to themselves and to the industry through the co-operation of their best men in the work of the various committees. Membership on these committees brings out the best that is in a man. It makes the man more valuable to his company, and at the same time it gives the industry the benefit of the man's experience, initiative and advice. I make an earnest plea to all electric railway companies to volunteer the services of their best men for committee work, believing it to be of the greatest importance to the entire industry and of great benefit to the men themselves, as well as to the respective companies.

The future of the electric railway industry will be determined largely by the intelligence, vigor and enterprise of the transportation companies themselves. That the future is secure I am certain, but it can be made doubly so by full co-operation throughout the industry. This co-operation can be made evident by active membership in the Association on the part of all companies and persons comprising the industry, and by participation in committee activities by the men who are having such a large part in carrying on successfully the service of the industry to the public.

# Some Problems of the Modern Executive

JAMES P. BARNES
First Vice-President, American Electric Railway Association
President, Louisville Railway Co.

SERVICE—held as the keynote of every organization aspiring to expansion and satisfactory monetary return to its investors—is the very foundation of the system or plan on which successful operation of street railways is built. To serve well is to build well.

Railways, through many lean years of competition, expensive legislation, heavy taxation, high prices and low rate base, are today following the path of consistent good service down the proverbial rainbow to the pot of gold—in other words a realization on the capital invested.

Speed with safety, comfort with economy, courtesy always, tend to increase car riding, and one of the chief problems confronting the executive today is to bring about a better relation between the possible patron and the corporation, with a view to increasing the car riding habit in the community. Volume of business, it matters not whether it be selling mouse-traps or street car tokens, is the secret of the successful operation of any business.

To stimulate the car riding habit on a laggard line (and what property does not have one or more?), as well as other lines, brings into the railway game a comparatively new and an important factor—the publicity director. As in all businesses of any magnitude today, the modern maxim 'It pays to advertise' is gradually being sold to progressive railway executives. Possible patrons must be educated to the advantage of cheap transportation plus a maximum of safety, convenience, and comfort. This is a situation brought about by the advent of the automobile. Attractive advertising well placed has built up the automobile business, and the up-to-date railway operator must meet existing conditions by putting before the public campaigns of interesting advertising in order that the industry may reap the reward due it.

Modern equipment and management are the foremost advertising agents of the industry, and when the public realizes our desire to modernize service and give them the best possible, it cannot help but bring about a confidence in the local utility that will be beneficial to all concerned. Although some people dislike to admit it, the life of the community is, to a great extent, centered about the electric railway company which serves it. The utility is a factor for the general good of the city, and what affects the citizen affects the railway; hence the desire of the railway companies to secure the confidence of the people they serve.

The need of many of our railway companies today is larger capital to finance this modernization movement, and to secure this they must first have the confidence of the new investor who, if he is confident of the company, may even be the joke maker's hero, a strap-

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hanger. Through the lean years, railway stockholders have been satisfied to receive a low return on the money invested, because they had confidence in the men at the head. To the credit of the railway executives it can be said that this confidence was not misplaced, and the shareholders are receiving larger dividends with still larger in sight. Customer-ownership is a field that should not be given too casual consideration by the executive, for a large customer-ownership on the books of any railway company is an added proof of the confidence placed in the management by the users of the service, and this adds weight when the company must adventure into larger fields to acquire additional capital.

Confidence founded on service is an ideal worth striving for. The pull may be a hard one, but in the Bible phrase "the reward will be great".

## Are We Too Near the Trees to See the Forest?

PAUL SHOUP
Second Vice-President, American Electric Railway Association
Executive Vice-President, Southern Pacific Company

ONE of the greatest benefits that could come to the present operators of electric railways would come about if they might in some way gain a detached outlook on their properties and the relationship of these properties to the communities served; to get a mental airplane view, in other words. Many of us are so close to the many problems confronting electric lines that we may not keep the proper perspective.

The first thing to do on gaining this imaginary vantage point is to ask: "Are we rendering a beneficial and necessary service to the public?" Assuming that we are justified in answering this in the affirmative, let us take stock of the situation.

We of the electric railway business have encountered many discouraging obstacles. To say that we have solved them all in a manner entirely satisfactory to all involved would not be in accordance with the facts. It has been a constant struggle, many times resulting in the best compromise obtainable. For this reason we may have lost a part of "that something" which enables the continued operation of a successful business.

We have seen increasing pressure from new forms of competition, mounting costs of operation, and greater burdens imposed by political subdivisions of the state; in spite of which we see on every hand new ideas being tried, economies achieved and, on the part of management, a vigorous will to surmount these obstacles.

While the records for 1927, and for the early months of 1928, cannot be viewed with satisfaction, there is some hope for betterment to be found in the improvement evidenced in relationships between the public and the electric railways. Municipal ownership in this field is becoming more generally recognized as an experiment by Seattle and other cities, and their records are being compared with operating economies and improved service under private management.

During 1927 large investments were made in new and more efficient cars and equipment. Comfort and convenience for our patrons has been advanced materially. Experiments with lower fares, and with the weekly, monthly and Sunday pass are being conducted with promising results by a number of railways. One of the bogeys is idle equipment during off-peak hours, and these experiments are proving beneficial.

Through newspaper advertising and informatory bulletins displayed in the cars, our patrons are gaining a more sympathetic insight into our problems, and this work, to be effective, must be continued. Better understanding between the electric railways and our employes has raised the standard of courtesy to a very satisfactory level, and its benefits are felt by management through the increased friendship of our patrons.

Regardless of what the future may hold for the electric railways, one fact is definitely indicated. The problems of the electric railways, aside from such major issues as relief from excessive taxation and the paving of streets and highways, are acutely localized, and must be solved through the experiments of the individual companies.

Probably no other industry, faced with problems so critical as those which confront us, has ever manifested greater or more intelligent determination to surmount obstacles. We know that electric railways are necessary and useful factors in urban and interurban transportation, and cannot be dispensed with. The difficulty is to determine and record a rate sufficient to maintain, and to permit improvements upon our present service. Whether or not this return can be secured through lower rates as an inducement for increased patronage, or through higher rates for the existing traffic, will have to be determined by each company. Local conditions vary greatly in various communities and the plan that is successful in one city may not work at all in another.

The merchandizing of transportation through advertising and solicitations is of growing importance and is given the careful study and attention it warrants by the more progressive companies. Well prepared advertisements, appearing regularly in the newspapers, develop patronage and help mould public opinion along favorable channels. But these efforts must be backed up by the very highest possible standards of service. "By their works ye shall know them."

The fact that in 1927 the net operating income of 322 larger companies showed a decrease of only $2 279 000, or 1.43 percent, although the gross revenue decreased $10 152 000 (a saving of $7 873 000 in

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operating expenses), indicates the extent to which good management has been able to affect economies and efficiencies. This decrease in revenue does not in any way tend to show that we are doomed to failure in our efforts to place the electric railways on a sounder financial basis.

In some smaller communities the privately owned automobile has tended to make street car operation and bus operation permanently unprofitable. In many other communities the one-man car has helped effect economies that make profitable operation feasible. But just as the modern skyscraper would be impractical were it not for high-speed elevator service, so the modern city would be handicapped if unaided by well equipped, efficiently managed and adequately financed electric railways.

When this fact is comprehended by public bodies and by the individual citizens, and wider recognition of the efficiency and integrity of the electric railways is won, many difficult problems now confronting us will be far nearer to satisfactory solutions.

## We are Not Trying to Get Higher Prices for Shop-Worn Goods

J. H. HANNA
Third Vice-President, American Electric Railway Association
President, The Capitol Traction Co., Washington, D.C.

PRACTICALLY all urban transportation companies are confronted with steadily decreasing traffic and corresponding reduction in net income, making it imperative for many of them to apply for higher fares. The granting of relief has been fought in many instances on the ground that street car transportation as now furnished is unpopular and that an increase in price for a service which is no longer in the public favor, is bad business practice.

There is, however, a vast difference between the case of the merchant who has on his shelves goods that were manufactured and purchased at some previous time and which have become out of date and unpopular and the case of those responsible for furnishing city transportation service, where the commodity is not held in stock but must be manufactured day by day and offered for sale whether any purchasers appear in sufficient numbers to pay for the service or not.

It is a well known and firmly established fact that losses in revenue due to a reduction in the number of passengers carried on a street railway can only be met to a very slight extent by curtailing service. The amount of service furnished by street railway companies is governed by two separate factors:

First—Non-rush service, the amount of which depends upon base headways; headways that are determined not by the volume of traffic to be handled but by the length of time passengers are required to wait for cars. Longer headway spacings naturally have a direct bearing on the number of passengers carried, for people will ride where the maximum wait, in city service, is not over six or seven minutes, but will turn to other forms of transportation if longer waits are necessary.

Second—Rush hour service. Here to a limited extent the service furnished is proportioned to the traffic demands, but the necessity of providing satisfactory working conditions for trainmen prevents any adjustment in the cost of service which is even approximately proportional to the loss in revenue. Moreover, it is the experience in most cities that the rush hour travel is not decreasing in anything near the same proportion as that during other periods.

The question of whether the rates requested exceed the value of the service furnished to the public has been raised in many fare cases, but experience in cities where a flat ten cent fare is in effect would indicate that certainly, until that rate of fare is exceeded, no consideration should be given to this phase of the matter.

Regulation prevents large profits in the public utility business and it is the duty of Commissions to fix rates so that the owners of property put to public use will be assured sufficient return to maintain their credit, provide for the continuance of existing service and, in addition, be able to improve its quality and provide extensions when and where they are needed.

It has been clearly shown that flat rates of fare in our metropolitan centers are desired by the public, so the price paid for short rides must be sufficiently high to cover the unavoidable losses on the longer ones.

The only solution of the problem in the best interests of the public, as well as the stockholders, is the co-ordination of all forms of urban transportation with regulation of a far-sighted and wise character which will not merely permit but encourage better transportation service for the great bulk of riders, with a different service on a different fare basis where conditions warrant.

## Better Transportation

CLINTON E. MORGAN
Fourth Vice-President, American Electric Railway Association.
Vice-President & Gen. Mgr., Brooklyn City Railroad Co.

WITH the restoration of confidence and optimism in the transportation industry, we still have before us the question, "Are we meeting the demands for better transportation?" The transportation agency that has honestly and energetically undertaken to improve the service it gives to its public to the extent that its service is as good or better in every way than that offered by its competitors has little difficulty in attracting new capital for the purpose of expanding or improving its transportation facilities. When this capital is intelligently expended the results are improved public relations, increased earnings and decreased operating expenses.

In few industries does the manufacturer play so important and intimate a part as in the electric railway

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industry. When the operator is in difficulty, he does not hesitate to call in his manufacturer friends. Particularly during this readjustment period, there should be closer co-operation between the manufacturers serving the industry and the operators in order that the ride supplied by the transportation agency will be considered the best by the public it serves. The quality of the ride should be of such character as to attract more riders and cause those using the service to feel that it is not only a pleasure, but it is also profitable for them to ride, instead of feeling that they are forced to use the service. When the public is in the latter frame of mind they will naturally avoid the street car as much as possible.

Much has been accomplished in the way of adding new cars and re-habilitating cars of older types, but there is still room for material improvement in the quality of the ride and the cost of producing it.

Safety, comfort, speed and regularity are the essential factors most vital to the riders, as the ride is considered from this angle by the patrons. When transportation is furnished by means of a modern vehicle well maintained, painted and clean, operating on smooth tracks, the results are obvious. It is in the maintenance of this vehicle, track and overhead structure that the operator needs the co-operation of the manufacturer with his organization so as to produce the ride at the minimum cost.

Modern rolling stock, both cars and buses, operating in a co-ordinated service are big factors in the production of the satisfactory ride but, unless this equipment is maintained properly, the attractiveness of the service will depreciate rapidly. In order to maintain the equipment properly, adequate shop facilities, including modern tools and labor saving devices, are required. To modernize our industry, not only should our older cars be replaced with modern equipment, but also our shops and other maintenance facilities should be re-habilitated if we expect to maintain adequately our equipment at minimum cost.

Primarily the electric railway organization is a transportation organization and not a manufacturing plant where a product is produced and placed on the market in competition with like materials and designs. It is here that the manufactureres can aid the industry by assisting the transportation executives, not only by improving their products supplied to the industry, but also by recommending to the transportation companies the best shop practices for taking care of their equipment.

The task of cleaning vehicles used in transportation has not been given the proper consideration either by the manufacturers of apparatus or by the operating executives. Cars are being cleaned today by the same methods used in the days of the horse car. We are lacking the proper shop tools in our maintenance shops. We have also failed to humanize our organization to the extent that the personnel have a clear understanding of the work in hand and the problems before the industry. Until these important factors are modernized and the personnel humanized we cannot expect to maintain our position in the industry.

From experience we find there are many improvements yet to be made in the equipment as now produced for use of the transportation agencies in supplying the car ride. These products require further scientific analysis and application. One need only to call attention to the rapid strides made by the automotive industry both as to materials used in their product and the ever changing designs. Although the electric railway industry is much older than the automotive industry, the progress of the latter has been more rapid than perhaps any other industry, including our own. If we are to remain the leaders in the transportation field we also must be progressive in all of our departments.

## Local Transportation Conditions in the United States

LUCIUS S. STORRS
Managing Director,
American Electric Railway Association

If one were to seek an answer to the query, "How about local transportation conditions in the United States?" he might paraphrase a popular song and say, "Old Man Transit just keeps rollin' along." When you analyse the situation impartially, you find the reason public transportation keeps rollin' along is that there is an insistent and growing demand for it. If this demand did not exist, it would not keep going. The industry is running 75 000 electric railway cars and almost 10 000 buses, the combined service covering some 60 000 miles of local passenger routes. By this coordinated service, something over 16 billion persons are being carried annually.

With this convincing answer to the inquiry as to the necessity for local transportation, it certainly is high time that managements, banks, owners of transit securities and others quit marking time on the theory that maintaining a foothold is their chief problem. Too many persons in the industry are thinking in terms of "hanging on." Do not understand by that last statement that the industry as a whole is not going forward. It is, indeed, in many respects. The progress it has made during the last ten years, and particularly during the latter half of that period, has been remarkable. Fares have been adjusted, service has been modernized and public relations have been greatly improved.

The modernization movement which has been extended to many cars should be passed on in other directions. Thorough scrapping of useless rail lines, with substitution of buses when necessary, and total abandonment when justified, would be a real progressive step. Properties which have done this without fear or favor have quickly noted the differences in their net income. And, after all, net income is the

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real measuring-stick of the prosperity in the industry. No matter how many passengers a company carries, if results do not show in the net, then its efforts have been futile.

Analysis and readjustment of personnel along the same lines used in strengthening weak lines should follow. There is no gainsaying the fact that no industry can be stronger than its weakest link. And the local transportation industry should look the facts of personnel squarely in the eye. Coincident with this readjustment process should come, commensurate compensation for the efficient.

Fares have gone up, but few will say that they have been adjusted on a scientific basis. The only just fare arrangement is the one under which each man pays fully for service rendered. The property owner who benefits by local transportation lines, even though he does not ride them, should help pay.

These three steps are highly important. Any one of them should keep the average management fairly busy during the year 1928. And when 1929 comes around, there doubtless will be other things to do. There usually have been in the past. The future in local transportation, probably long will hold out attractive opportunities for willing workers who thrive on keen competition.

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# The Engineer in the Electric Railway Field

R. H. DALGLEISH
President, American Electric Railway Engineering Assoc.
Chief Engineer, The Capital Traction Co., Washington, D.C.

WHILE the engineer in the past few years has tackled and solved many of the difficult problems that have confronted the electric railway industry, his job has just begun for there are other problems that are crying for some one to master them, and in the future development of public transportation, situations will constantly arise where his training and experience will be brought into play.

Whatever the ability of the individual engineer, and however vigorously he has taken up the many complex tasks confronting him, it would be unfair to minimize or fail to mention the important part that has been taken toward the solution of many problems by the American Electric Railway Engineering Association. Its work has not only resulted in benefiting the industry as a whole, but has unquestionably helped the individual engineer who has been able, through participation in Committee meetings, to engage in that exchange of ideas which leads to progress in all lines of endeavor.

The problems that face us today, that faced us yesterday and will be staring at us tomorrow, have been and will be much the same whether in Seattle or Jacksonville, Bangor or San Diego. First hand information from the other fellow, as to how he handles a situation, cannot fail to be beneficial, so that I am desirous of impressing railway engineers with the advantages that may flow from him and back to him and his company, because of his assistance in the work of the Engineering Association. What any one of us puts into that work is far outweighed by what he gets out of it, for the information that is collected and approved by some of the outstanding engineers of the industry is available to all engineers through the Association's publications.

Mention should be made of the fact that the United States Bureau of Standards has been co-operating with the Association with gratifying results, in considering some of the vexing questions that have come up. This co-operation has been whole-hearted and friendly with a very evident desire, upon the part of those who have taken part in tackling our problems, to be of real service.

During the current year, 25 special committees were appointed to study special subjects. Some of these committees worked in co-operation with the Bureau of Standards, with members of other engineering societies or associations and the Department of Commerce. Members were chosen from among the engineers of operating companies, engineers connected with manufacturers and professors of engineering of leading schools and universities. The engineering staff at Association headquarters materially aided these committees. What the Association is doing may be suggested by a brief statement of the subjects assigned to this year's committees, which included:—

*Way and Structures Division*—Thirty-two subjects pertaining to construction and maintenance of track and buildings.

*Rolling Stock Division*—Twenty subjects relating to construction and maintenance of equipment.

*Power Division*—Eighteen subjects pertaining to the generation and distribution of power.

*Purchases and Stores*—Eight relating to the purchase and distribution of materials.

Out of the many problems that are before us today, I should like to mention one, because it appears to me to be of some importance. That is a car that can be operated more quietly. To bring about that result, there is need not only for cars that make less noise, but for track structures that will contribute to smooth riding. There undoubtedly must be also the best shop facilities for proper inspection and for adequate mainenance. The best equipment, no matter how well it has been designed and constructed will become noisy, inefficient and expensive to run, if it is not properly maintained.

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# Handling Mass Transportation

JOSEPH H. ALEXANDER
President,
Cleveland Railway Company

PERHAPS the most serious problem confronting the street railway companies, operating in large cities, is the service at the evening rush hour. It is an open secret that the private automobile is cutting dangerously into the car riding habit. Each year the drop in the number of riders continues; and although many feel that the bottom has been reached and our records will begin to show an increase, no evidence is forthcoming convincing enough to establish this as a certainty. The automobile owner knows that his transportation to and from work is costing much more than a street car ride, yet because of the greater speed and comfort, he seems willing to continue. There is no doubt that he would be better off were he to ride on a street car to work, irrespective of the cost. Generally speaking, in the morning he can get a seat, read the newspaper and be free of all driving anxiety and parking difficulties. The difference in traveling time, in my opinion, is not sufficient to make him prefer the private automobile. In the evening it is quite different. In a much shorter space of time many workers have finished their daily work and must crowd into the street cars. The prospect of standing up more often than not, of being crowded as the street car travels slowly through traffic, is unpleasant enough to make the owner of the private automobile provide his own transportation.

Until the street railway company can offer the car rider reasonably satisfactory transportation, it should not complain of any falling off in traffic. In other words, when the present car rider is properly provided for, then will the time come to grow anxious over the decline in the number of riders. The merchants' slogan, "A satisfied customer is the best advertisement," cannot yet be applied to urban transportation; and until then inducements, however ingenious, seem to be in vain.

In Cleveland the problem is not peculiar. Indeed the bulk of the task of bringing the urban workers to and from their places of business falls on the street car, for comparatively few commute on the steam rail roads. We are attempting to meet our obligation to the car rider by the development of an improved type of car. The articulated train provides a rate of acceleration sufficient to keep pace with the automobile and, for those fortunate enough to find seats, as great comfort. Besides, this unit holds out the hope that the same number of trainmen will be able to provide greater service, that is to say, two men can handle what formerly required three, and thus one-half greater carrying capacity is available per man.

Further ameliorating conditions can be effected. For instance, due to a growing belief in the community that the difficulty of mass transportation is a city and not exclusively a railway problem, a start has been made in staggering the working day. That is to say, the working day is begun and ended at different times in some establishments, so that the heavy transportation load is distributed over a greater interval of time. As it was in the early history of "daylight saving", the inertia of custom is great, but it should not be an impossible feat to bring about a result beneficial to all concerned.

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# Opportunity in the Street Railway Industry

W. T. ROSSELL
General Manager,
The Pittsburgh Railways Co.

THE rise of industrialism and trade and the growth of cities are interdependent. Transportation and communication are the means of their existence. Mass transportation, within the modern city, must be adequate or all the people suffer. Through the slow and painful process of trial and error, each kind of transportation will find its proper place and use. Rapid transit, the street car, the bus, the taxicab, the private automobile, the elevator and the pedestrian, each must do its share.

There is nothing more important than this problem, and its solution needs the best that can be secured in technical skill and administrative ability. The college trained man has before him a wide field for choice of occupation. Through invention and the advance of science, whole new industries are growing up with surprising speed, while the increasing needs and desires of the people are developing older industries to greater and greater size.

The street railway bears the greater part of the burden of mass transportation within the city. The forms of work included in its operation are greatly varied, comprising engineering problems, both construction and maintenance of track and equipment, transportation and traffic regulation, accounting, purchasing, public relations, and legal and research work. Therefore, the street railway industry offers an exceptionally wide experience to the individual engaging in it. Employment is steady, since the street cars must operate continuously. Working hours vary with the type of work undertaken.

The remuneration depends on the specific work performed and the rates of pay in effect in different companies. While in the past the street railway has not equalled manufacturing industries in financial rewards to its executives, there has been some improvement recently in this respect, which will no doubt continue.

There is also the factor of wide acquaintance in the community, which naturally accrues to the street railway executive and frequently opens the door to opportunities in other directions. On the other hand, the element of competition cannot be overlooked. In a large number of employees, only a few can reach the highest positions in the industry. This is equally true,

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of course, in all fields of endeavor. The street railway offers steady and interesting employment and its opportunities are worthy of consideration by the young man entering industry.

## Analyzing the Future

G. C. HECKER
Special Engineer,
American Electric Railway Association.

EVERY electric railway official is familiar with the difficulties with which the industry has been beset in the last ten years; and with the splendid way in which these problems have been attacked, and in a considerable measure solved. One great good that has resulted from this period of stress has been the definite demonstration that public transportation in all but the smaller communities is an absolute essential. If it had not been, the industry never would have survived the revolutionary period through which it has been passing. A world of credit is due the men who have operated the electric railways of the country through this period of rising costs of operation and intense competition.

Most of the remaining problems are of an engineering nature. Thorough, painstaking surveys and intelligent engineering study and analysis are absolutely essential to future success. No one is quite so well equipped to do this as the men who now operate the local transportation systems.

Is management fully alive to the vital necessity of surveying the future? A notable illustration of the value of such surveys is found in the healthy condition of the telephone industry. A definite, co-ordinated system of research and study of future communication requirements enables that industry to plan its moves years in advance, and to check its course from time to time. It is possible for the electric railways to chart their course similarly, and with a degree of accuracy that will enable the industry to adjust itself readily to changing conditions, whatever they may be. Few companies have adopted such a policy. Too many are drifting in an open sea on an uncharted course.

Are electric railway engineers awake to their opportunity to play an important part in this highly essential work? Or are they so hopelessly entangled in the details of their routine work that they overlook their larger responsibilities—those of leading the way in surveying the future and furnishing management with the information so vital to the prosperity of the industry?

Forecasting the future is not a simple task. On the contrary it is one requiring the highest type of engineering skill, A carefully-considered and well-planned method of approach to each of the problems is all important. Voluminous data on every phase of each problem must be compiled from which trends may be determined. The relation of each problem to the others must be carefully considered. Many variable and unknown factors complicate the task, and probably will result in forecasts requiring the charting of more than one general course for the future, each being based on certain contingencies.

Such surveys and analyses must be periodically checked and the course recharted in accordance with the conditions found to exist at those times. Companies that have followed this practice for years have found it an invaluable aid in planning intelligently for the future. It is to be hoped that the practice will become wide-spread.

## Developments in Street Car Drives

G. M. WOODS
Street Railway Engineer,
Westinghouse Electric & Mfg. Co.

THE interest in new forms of street car propulsion shown at the Convention of the American Electric Railway Association last year is one of the signs of the progressive spirit of the industry. The worm-drive cars of the Springfield Street Railway and Chicago & Joliet Electric Railway, the 1928 Model Brill car with the new W-N drive and several trucks with modified worm drives were exhibited. Since that time a number of cars have been equipped with worm drive, a number with W-N drive, several other drives bearing a certain relation to these have been tried experimentally and doubtless other new drives will make their bow at the 1928 Convention.

The reasons for the intense interest in new drives are not hard to find because the best engineering minds of the industry have been searching for a form of propulsion that would respond more fully to modern demands. These demands are for less weight, less noise, less unsprung weight, greater clearance under the motors, smaller wheels, elimination of the old style gear case and axle bearings, and, above all, higher schedule speeds.

While most railway operators and transportation engineers are confident that the street car has a long and useful life ahead of it and can see no satisfactory substitute on the horizon, they frankly admit that the street cars in service today are far from perfect vehicles. Private automobiles, which thrive particularly well on American soil, have created a demand for a type of transportation superior in many ways to that afforded by most of the existing street cars.

While its business is not advancing as it should, the electric railway industry, including operators and manufacturers, is not remaining idle and consoling itself with thoughts that the high cost of private automobile operation, parking difficulties, and congestion will eventually bring back the lost patrons and that all that is needed is a little patience. On the contrary no

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established industry has ever more completely changed its methods or sought more diligently for improved equipment.

Among the first evidence of an awakened desire for improvement was the change from a "take it or leave it" policy to one of active merchandising. Another was the substitution of a frank discussion of problems for that of "nothing to say". Others were customer ownership, higher schedule speeds, more frequent service and more luxurious furnishings.

Even where the most progressive operators had done all these things, they found that something was still lacking. As a result they analyzed the street car more thoroughly and found that it was heavy compared with automotive vehicles, it was noisy, it was too slow, it pounded over special work, the simple drive in vogue had certain inherent undesirable characteristics, and the floors were high, causing slowness and inconvenience in passenger interchange.

However, the foremost need was higher schedule speeds. Mr. E. J. McIlraith, Chicago Surface Lines, says, "The failure to increase the average speed of operation is one of the major factors in preventing an increase in business in most cities. In order to maintain a high average speed it is necessary to have adequate motor capacity. High accelerating rate and high free running speed are needed if the street car is to compete successfully with any vehicle in the street. With the faster car the standard of service on a line can be maintained with a smaller number of cars and consequently a lower cost for housing, and the cost of operation in trainmen's hours also is reduced."

It is not the intention to imply that all railway operators have made the best use of their existing car equipment—in many instances railway service can be improved appreciably with existing equipment. Neither can it be said that all operators in the recent past have purchased the best equipment available. There are in service too many antiquated, inefficient cars which have been running twenty years or more. The problem of financing new cars is difficult.

Since the advent of the Birney safety car, efforts have been made to reduce the weights of cars; and with lighter cars came the more general use of low floors and quadruple equipments of motors. The railway properties which purchased cars of this type are as a whole the most prosperous today. Frequently the way to make money is to spend money. Economy and penury are often confused.

Vast improvement that these new cars really were, with changed conditions, they do not entirely meet the demand of today. The new drives are a great step toward the perfect street car. The article by W. A. Brecht in this issue of the JOURNAL describes the W-N drive in detail. Attention is called to the improvements the W-N drive effects, compared with axle mounted motors, and how each one of these improvements overcomes some objection to the standard form of street car.

First, the equipment with W-N drive weighs a ton less per car than axle mounted equipment with motors of the same rating. Other characteristics of this drive permit car design features which save another ton or more of car weight.

Second, the motors and gear units are practically noiseless. The construction is such that quiet operation can be expected throughout the life of the unit.

Third, the low weight per horse-power permits of additional power for any given weight of car, or lower car weight for any given horse-power. The results are increased rates of acceleration, higher free running speeds and increased schedule speeds.

Fourth, the unsprung weight is reduced. This results in less noise when the car is passing over special work and in less wear and tear on the track as well as on the motors.

Fifth, the new drive maintains accurate gear centers throughout its life. The numerous troubles due to the axle bearings of axle-hung motors are eliminated. The gears run in a bath of clean oil and the troubles incident to the split gear case are avoided.

Sixth, the 35 hp motors with W-N drive have more clearance with 22 in. wheels than axle hung 35 hp motors have with 26 in. wheels. The lower floors thus possible make passenger interchange easier and faster. This is pleasing to the public and a further contribution toward high schedule speeds.

It is apparent that the new drives are a valuable contribution to the electric railway industry. They afford a means of overcoming or avoiding many of the present-day street car ills. The manufacturers are addressing their efforts toward the perfection of these developments and the operators are placing orders for reasonable a number of these new equipments and are co-operating in working out the detail problems encountered. With the manufacturers and operators bending every effort toward perfecting the street car, this valuable transportation agency will come back to its former position of one of the most progressive and prosperous public utilities of the country.

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# The Development of the W-N Drive

W. A. BRECHT
Railway Motor Engineering Dept.,
Westinghouse Electric & Mfg. Co.

THE recent history of transportation in urban centers has introduced many new problems. The earliest electric street cars were ponderous affairs, slow of acceleration and deafening in action; yet they enjoyed a virtual monopoly of city and interurban transportation, and the industry flourished. These cars were equipped with split-frame, non-ventilated, non-commutating pole motors, and split, cast-iron gears. With the advent of the automobile and the growth of cities, with resultant increasing transportation demands, the modern box frame, ventilated motor and one-piece, forged-steel gears were developed. Then, with the post-war development of the bus, a new factor has entered into the transportation problem. The railway industry, as a result, finds itself in a position where it must actually sell street car transportation to the public. To succeed, street cars must be made more attractive to the prospective rider. Aside from improvements in body design, the best ways of accomplishing this are by securing quietness of operation and high schedule speeds, with smooth and rapid acceleration and braking. Because of mounting costs and competition, the operator is also vitally interested in economy of operation.

The W-N drive was developed to meet these conditions. It consists of a light-weight, high-speed, completely spring-borne motor driving an axle-mounted, self-contained gear unit through a flexible universal joint. It is made in two sizes, thirty-five and fifty horse-power. Gear ratios up to 10:1 are available, and wheel sizes of 22 and 24 inches respectively on the 35 and 50 horse-power units can be used with ample road clearances. A 35 horse-power unit mounted in a truck is shown in Fig. 1.

The motor is mounted parallel to the axle and between the axle and the truck transom. It is swung from the truck structure by two vertical links in its axial gravity plane. This permits of the use of a single universal joint between the motor and gear unit, instead of the conventional double-coupling arrangement. The motor pivots about its trunnions during angular misalignments between the motor shaft and the high-speed pinion shaft of the gear unit, so that the center lines of these two shafts always intersect within the coupling. No lateral misalignment of the two shafts is possible.

The nose, or driven end of the gear unit is suspended from the truck structure by a link which serves two purposes; it transmits the gear torque reaction from the gear unit to the truck frame, and it maintains the alignment between the high-speed pinion shaft and the motor shaft. The center of the link is on the center of the high-speed pinion shaft. This means that the gear unit pivots about its high-speed shaft as the axle moves up or down with respect to the truck structure, and that the lateral alignment between the motor shaft and the high-speed pinion shaft is entirely unaffected by journal spring deflections. Hence, the only misalignment which can occur is angular, when the axle gets out of parallel with the motor shaft. Such a condition is experienced only when track inequalities or curves cause unequal deflections of the journal springs. This is usually of short duration and imposes but slight duty on the flexible coupling. During ordinary operation on straight, smooth track, the motor and pinion shafts are in alignment, except for such slight inaccuracies in the truck mounting as may exist.

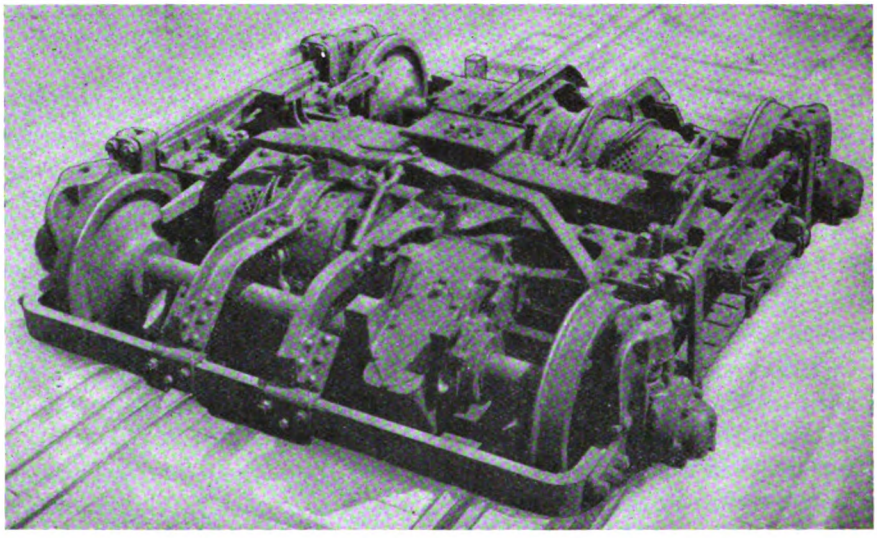

FIG. 1—TWO 35 HP MOTORS AND THE W-N DRIVES MOUNTED IN A TRUCK

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The entire weight of the motor and coupling, and about one-half of the weight of the gear unit, are spring suspended. The dead weight on the axle is thus greatly reduced. Smaller wheels can be used, which further reduces the dead weight on the axle. This results in a sharp reduction in the force of the hammer blows experienced as the wheels pass over bad rail points, etc., and hence, decreases the vibration and

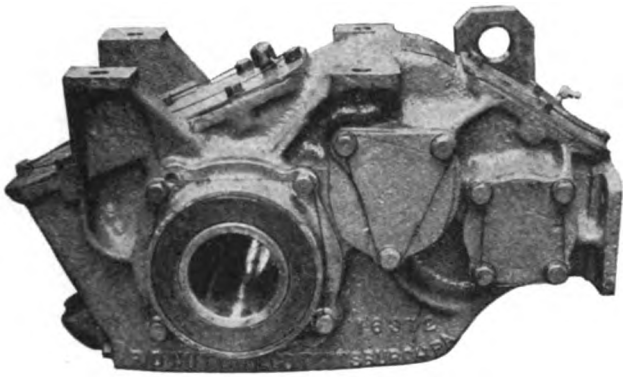

FIG. 2—A VIEW OF A 35 HP W-N GEAR UNIT FROM THE WHEEL SIDE

stresses on the motor and on the truck structure as well. It greatly reduces the noise caused by such impacts. The principal troubles encountered in the operation of railway motors are of mechanical origin, resulting from the severe vibrational stresses experienced in railway service. These troubles include chafed coils, broken coil springs and loose coils, broken leads, chipped brushes, worn bearings, etc. The conventional box frame, axle hung motor, in addition to having one-half of its weight a dead weight on the axle, and hence, subject to the hammer blows and severe vibration set up by bad rail conditions, is also subjected to severe torsional vibrations. These vibrations are caused by gear inaccuracies, and are aggravated by the fact that the pinion is mounted directly on the motor shaft, and is overhung from the motor bearings. In the W-N drive, no overhung pinions are used. Since the gears are held in accurate alignment and the center distances accurately maintained by the gear unit roller bearings, very little torsional vibration is set up. In addition, the coupling between the motor and gear unit is flexible torsionally, and protects the armature from any torsional impacts. Thus the W-N drive motor is protected from impact forces and vibrations of all types.

## THE GEAR UNIT

The gear unit is shown in Figs. 2 and 3. The gear case is a one-piece steel casting. Light weight, ruggedness, and compactness were prime factors in its design. Another important object was to use oil lubrication of the gears, which imposed the additional problem of sealing the unit against oil leakage, and against the entrance of dirt. By running the gears in a bath of clean oil, greatly increased life can be expected.

In designing the gear unit the use of a split gear case was considered. Such a construction has the apparent advantage of making the assembly and disassembly of the unit, and its removal from and application to the axle, easier of accomplishment. To offset this the split construction has several disadvantages. It would be extremely difficult to keep the split oil tight, requiring accurate machining of the gear case halves, and the use of a gasket between them. After repeated assemblies it would be practically impossible to seal such a unit against leakage. One of the chief factors was light weight. A split case cannot be made as light as a one piece case, and still retain the required strength and rigidity. The W-N gear unit has been so designed that the high-speed pinion can readily be removed and replaced while the truck is under the car body, and without disturbing any other gear unit parts. Since none of the other gears will require replacement except at long intervals, the apparent advantage of the split construction becomes questionable.

Double-reduction is used in this unit with high angle helical gears. In order to secure a minimum of torsional vibration, the helix angle and width of face were so chosen that three teeth are always in contact at the pitch lines. The gears are mounted on six tapered roller bearings. Two of these carry the high-speed pinion shaft, one on each side of the pinion. Two more carry the intermediate shaft on which the high-speed gear and the low-speed pinion are mounted. The low-speed gear, instead of being mounted directly on the axle, is pressed on a hollow sleeve which is mounted in the gear case on two more roller bearings. This construction results in a self-contained unit which is pressed on or off the axle without disturbing the

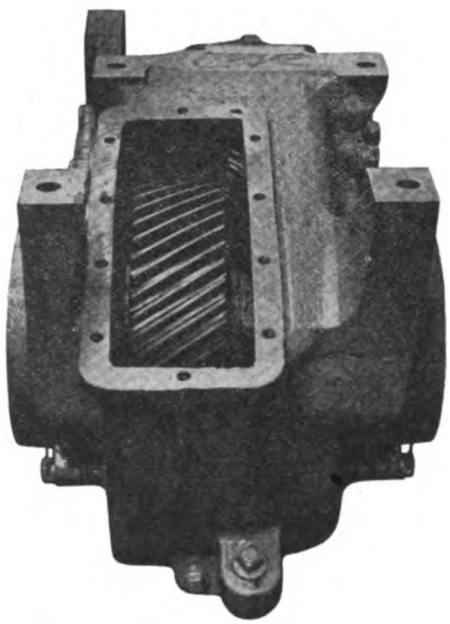

FIG. 3—A 50 HP GEAR UNIT, LOOKING AT THE AXLE END, COVER REMOVED

assembly. It is no more difficult to assemble a unit on an axle than to press an ordinary gear on or off. The two gears have cast iron rings pressed under their rims. This makes them so "dead" that when struck they emit little more ringing noise than would a piece of lead. This feature was adopted after considerable research into gear noises with delicate noise measuring

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instruments. No gear noise has been evident on any cars equipped with W-N drive during any part of the operating cycle.

The bearings are lubricated by the oil splash from the gears. Shims behind the bearing caps permit adjustment to compensate for such wear as may occur. The oil seals provided are so effective that on the units now produced, no leakage of oil from the unit is apparent. A medium grade of unblended automobile oil is recommended.

Efficiency tests on the gear units are shown in Fig. 4, together with the standard A. I. E. E. efficiency curve for single-reduction gearing. It will be seen that at loads greater than the one-hour rating of the motor, the gear unit efficiency is greater than that of single-reduction gearing. This is a most desirable condition where high acceleration rates are desired. It reduces the peak current drawn during the accelerating period, which is highly desirable during rush hour operation where a large number of cars are in service. At loads under the one-hour rating the rotational losses become

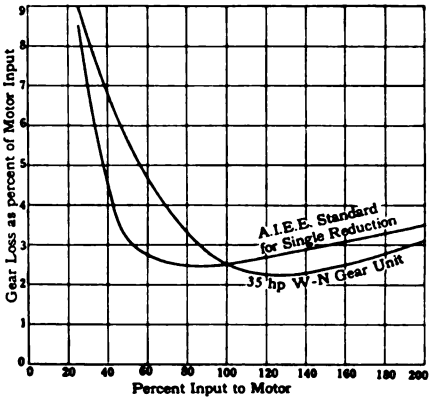


FIG. 4—COMPARATIVE GEAR LOSS CURVES

higher and result in a somewhat lower efficiency for the W-N unit than for single reduction gears.

### THE COUPLING

The universal joint is of the thermoid disc type, similar to those used in automotive practice. It was specially designed for railway service, however, and is much more rugged than the couplings used on buses and trucks. It contains a centering device which permits only angular misalignments to occur at the coupling.

### THE MOTOR

As gear reductions of 10 to 1 are available in the W-N gear units, high-speed motors can be employed. Such motors have been developed in two sizes. The speed at the one-hour rating of the 35 hp motor is 2100 r.p.m., and of the 50 hp motor, 1700 r.p.m. The highest speeds at the one-hour ratings heretofore have been 1235 r.p.m. for 25 horse-power and 1070 r.p.m. for 35 horse-power. The new 35 and 50 hp motors are designed for maximum safe speeds of 5000 and 4000 r.p.m. respectively.

These high speeds result in motors of considerably smaller dimensions and lighter in weight. The trend in railway motor design has been constantly toward more power output per pound of motor. The curves in Fig. 5 show this trend graphically. Motor weights, complete with gear and gear case, are plotted against the one-hour horse-power rating. Three lines of

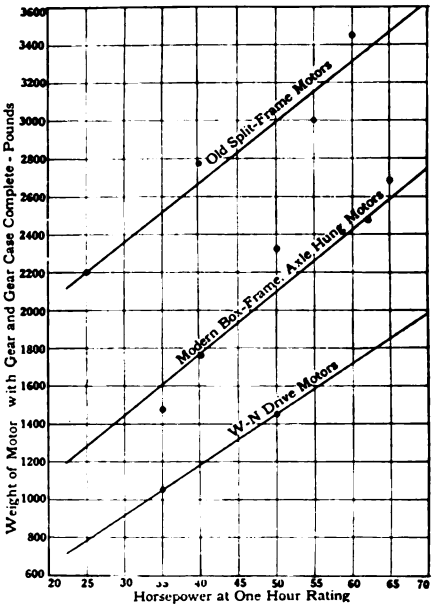
Weight of Motor with Gear and Gear Case Complete - Pounds
Old Split-Frame Motors
Modern Box-Frame, Axle Hung Motors
W-N Drive Motors
Horsepower at One Hour Rating

FIG. 5—THE TREND IN DESIGN IS TOWARD LIGHTER MOTORS PER HORSE-POWER

motors form three different curves. The upper curve represents the old, split-frame line, the middle curve the modern, box-frame, axle-hung motors, and the lower curve the W-N drive motors. Fig. 6 is a similar set of curves of motor weights plotted against tractive effort at the one hour rating. Since the W-N drive permits the use of smaller wheels than can be used with the box-frame, single-reduction motors, these

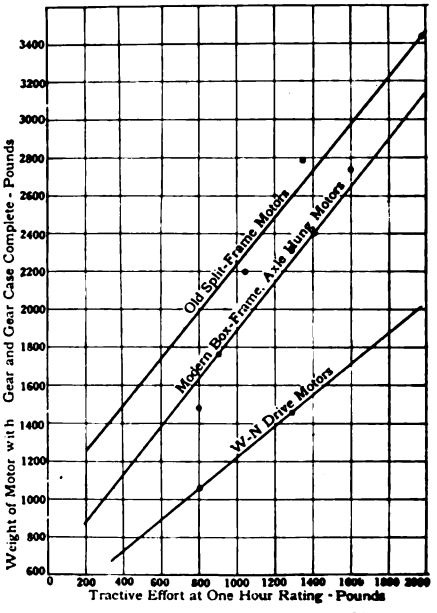
Weight of Motor with Gear and Gear Case Complete - Pounds
Old Split-Frame Motors
Modern Box-Frame, Axle Hung Motors
W-N Drive Motors
Tractive Effort at One Hour Rating - Pounds

FIG. 6—MODERN DESIGN GIVES LIGHTER MOTORS PER POUND OF TRACTIVE EFFORT

curves show even more strikingly the weight advantage of the W-N drive motors. Representative motors of the split-frame type (including gears and gear case) average 67.4 pounds per horse-power, as compared with 42.7 pounds for modern box frame motors and

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28.3 pounds for W-N drive motors. The bare motors used in the Cardan shaft drives in European service average 31.5 pounds per horse-power in weight, as compared with 15.5 pounds per horse-power for the bare motors used in the W-N drive.

In spite of this great reduction in motor weight, the W-N drive motors are as rugged mechanically as the modern box-frame motors. This is due to the high speeds used, to improvements in ventilation, to the use

FIG. 7—A 35 HP W-N DRIVE MOTOR ARMATURE

of class B insulation, and to the fact that the motors are designed to operate on 300 volts. The use of high speeds increases the ventilation of the motor armature and fields. By incorporating the principle of dual ventilation into the design, the ills often resulting from passing large volumes of air through a motor are avoided. These ills are caused by dirt carried with the ventilating air, which often causes rapid commutator wear and flashing. With dual ventilation the commutator space is totally enclosed, and none of the ventilating air passes over the commutator. Fig. 7 shows how ruggedly the armature of the 35 hp motor is constructed. The complete motor is shown in Fig. 8.

Two of the 300 volt motors are connected permanently in series. Motors of the rating and speeds used on W-N drives are more stable electrically and more rugged mechanically when designed for 300 volts. The smaller motors of the modern box-frame type, notably the 25 horse-power motors, are at the limit of good design for 600 volt motors as regards commutation. The chief factors to be considered in the design of a motor to obtain good commutation are the volts per inch of commutator, commutator peripheral speed and number of bars. In making a high-speed commutator, the diameter must be kept small in order to stay within safe limits of peripheral speed. This means that the number of volts per inch becomes large, and also the voltage between brushholders. The 300 volt design cuts the volts per inch, and the voltage between brushholders in half. It also reduces the number of commutator bars necessary for a good design. Each bar is, therefore, thicker and stronger, and the assembled commutator is rugged enough to withstand the high rotational stresses with a wide margin of safety.

Another advantage of the 300 volt motor over a 600 volt design is that the armature conductors are twice as large on the former. This means that the coils are strong mechanically and not easily damaged in handling. The large conductors afford a better foundation for the armature bands. Trouble from broken armature leads should be much less on the 300 volt construction because of the larger armature conductors. The W-N drive motors are insulated for 600 volts, since the motor on the trolley side would be subjected to that voltage to ground. Should one motor become grounded, or wheel slippage occur on one pair of wheels, 600 volts would be impressed on the other motor of the pair.

A question commonly asked is, will such excessive wheel slippage or a grounded motor cause flashing on the motor in series with the one so affected? It may, but experience has shown that these motors are so stable as to make this a rare occurrence. A precedent for the use of two 300 volt motors in series is seen in the applications using two 600 volt motors on 1200 volt lines, or two 750 volt motors on 1500 volt lines. These installations have been most successful.

Tests of an interesting nature have been made on W-N drive motors to prove their stability and the practicability of the 300 volt design. In Cleveland, the rails were greased under one axle and the controller notched up. The slipping wheels caused 475 volts to be impressed across the commutator of the motor in series with the motor driving them. No flashing resulted, commutation remained good, and the motor showed no distress of any kind.

In another test, a 35 hp motor was loaded to its one-hour current rating at 500 volts. The motor speed was 4000 r.p.m. which, with 22 inch wheels and a gear ratio of 8.45 to 1, corresponds to a car speed of 31 miles per hour. Commutation remained excellent. The same motor was then loaded so that after it reached its full speed it would be operating at the one-

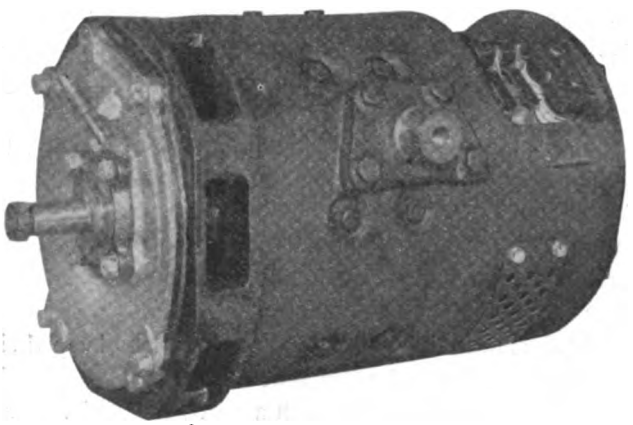

FIG. 8—A 35 HP W-N DRIVE MOTOR

hour rating. Then the motor was stopped and 300 volts applied instantly at standstill. The instantaneous current drawn was 200 amperes. No sparking or flashing was produced.

The efficiency curve of the 35 horse-power motor is shown in Fig. 9 superimposed on that of a modern box-frame motor of similar rating. The efficiency of the W-N drive motor is from one to two percent better

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throughout the entire operating range.

HIGH SCHEDULE SPEEDS

One of the objects of the W-N drive development was to increase the schedule speeds. Increased accelerating rates and braking rates are necessary to accomplish this result. Fundamentally, increased accelerating rates can be obtained only by increasing the horsepower capacity of the motors per unit of weight of the

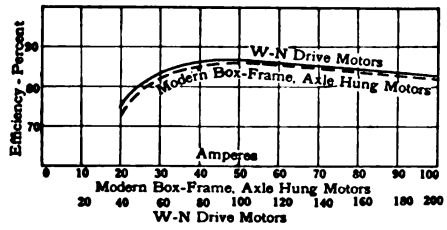
Efficiency - Percent
90
80
70
W-N Drive Motors
Modern Box-Frame, Axle Hung Motors
Amperes
0 10 20 30 40 50 60 70 80 90 100
Modern Box-Frame, Axle Hung Motors
20 40 60 80 100 120 140 160 180 200
W-N Drive Motors

FIG. 9—COMPARATIVE MOTOR EFFICIENCY CURVES

car. A reduction in car weight for a given motor, or an increase in motor capacity for a given car weight, are the only means of accomplishing this. The W-N drive, weighing the least of any street car drive per delivered horse-power, is one factor in obtaining light car weight. To get the best results all excess weight must also be eliminated from the trucks and car body.

Accelerating tests have been made on a car equipped with four 35 horse-power W-N drives. The loaded weight of this car was 33 000 pounds. Accelerating rates of three miles per hour per second were easily and regularly obtained. This is about the limit for passenger comfort. Accelerating rates as high as four and five miles per hour per second were realized during the tests. The ability to obtain such rates is of inestimable importance when operating in traffic, as every automobile owner will realize, although such high rates of acceleration as four or five miles per hour per second would be seldom used in actual practice.

Another means of speeding up car service is by lowering the car floor so that passengers can get on and off more quickly, thus reducing the time for stops. The 35 horse-power W-N drive permits the use of 22 inch wheels with one inch greater track clearance than its corresponding predecessor gives with 26 inch wheels. If the trucks and car body are properly designed, the car floor can be lowered by the amount the wheel size is decreased. The small wheels open a new field for the car builder in producing cars of beauty and attractiveness to the car rider since the low stream-lined appearance, popular in the automotive field, can be obtained.

# Speed in Street Railway Service

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THE popular notion conveyed by the word speed today is that of excessive speed or something upwards of 35 miles per hour. This is, of course, quite impossible for a complete trip between points within a city. Automobiles do well to make an average speed of 15 miles per hour between origin and destination within a large city. Street cars must make stops for passengers and yet can attain a speed that is reasonably close to that of automobiles in similar districts. Some street cars can run as fast as 35 miles per hour if there is a long distance between stops, but such maximum speed is of no particular interest. It is the average rate of operating between terminals that concerns electric railway operating men.

Unfortunately, many railways do not so keep their records or so control their schedule making and their operation as to know what such a speed record is. Many divide the number of car-miles by the number of pay-hours for the car crews and call the resulting figure the railway speed. Since such a method includes as part of the operating time, the lay-over time and all the allowances, it has really nothing to do with the speed of operation. The public is concerned only with the actual speed of movement between two points. Certainly it sounds ridiculous for street railways to be talking of figures which wrongly represent the speeds to be less than nine miles per hour. With proper scheduling and recording it would probably be discovered that the actual average operating speed on most railroads is above ten miles per hour.

By eliminating delays the speed for all railways could, doubtless, be raised well above eleven miles per hour without sacrificing safety. Then electric railway operation would more nearly approach the average speed attained by private automobiles making similar trips, and greater interest in railway riding would surely result.

The curves in Fig. 1 show that there is a definite limitation of the rate of speed that can be attained with a given number of stops per mile. It is surprising to notice how rapidly the horse-power requirements increase with an increased number of stops per mile for a given schedule speed. It is equally clear that the number of stops actually made per mile is one of the most important factors in determining the speed of operation.

The rate of acceleration and deceleration and the ultimate running speed of the car are important, but these must be kept within a reasonable range, in order that the passengers may have confidence in their ability to move along the car while it is in motion. If the rates are too high, the passengers are inconvenienced,

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and will not readily move to or from their seats except while the car is at rest. To gain the full benefits of increased speed of operation, passengers must be able to move quickly out of the way from the entrance of the platform, and should reach the exit door before the car comes to a stop.

An analysis of one line in Chicago to determine the effect of using two 65 hp motors as compared with

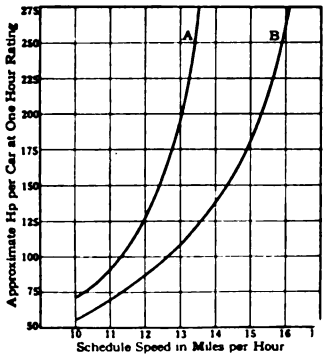


FIG. 1—INFLUENCE OF MOTOR POWER ON SCHEDULE SPEED

Curve A, 7 stops per mile.
Curve B, 5 stops per mile.
Weight of car loaded and equipped, approx. 26 tons.
Wheel diameter, 28 in. Average voltage, 560.
Four 40 hp motors.
Duration of stops, 7 sec. Coasting 150 ft. per run.
Rate of acceleration and braking 2.5 m. p. h. p. s.
Running friction, 20 lbs. per ton.
Coasting friction, 30 lbs. per ton.

four 55 hp motors has been worked out in great detail to determine whether it is economical or desirable to use the more costly equipment with a higher energy consumption in order to improve the speed. This line, Crawford Avenue, is a cross-town line, 10.7 miles long,

TABLE I—RUNNING TIME ALLOWANCES FOR TWO AND FOUR-MOTOR CARS
(Taken from a Midday, Weekday Schedule on the Crawford Ave. Line)

| | Distance in Miles | Minutes Allowed | |
|---|---|---|---|
| | | Two-Motor Car | Four-Motor Car |
| Bryn Mawr to Elston Ave. | 1 64 | 8½ | 7½ |
| Elston Ave. to North Ave. | 3 45 | 18 | 16 |
| North Ave. to Ogden Ave. | 4 02 | 21½ | 18½ |
| Ogden Ave. to 31st-Kostner | 1 46 | 7½ | 7 |
| Total | 10 57 | 55½ | 49 |
| Minutes per Mile | | 5 25 | 4 64 |
| Miles per Hour | | 11 43 | 12 92 |

CAR REQUIREMENTS

| Weekday | Two-Motor Car | Four-Motor Car | Reduction with Four-Motor Cars |
|---|---|---|---|
| Morning Rush | 83 | 74 | 9 |
| Base | 30 | 27 | 3 |
| Afternoon Rush | 79 | 72 | 7 |

having a headway of one minute in the rush hours, while during the middle of the day and early evening the headways are three minutes and four minutes. With the two-motor car the average accelerating rate is 1.88 miles per hour per second. With the four-motor car there is better adhesion on slippery rails and an average rate of 2.5 miles per hour per second can be expected. Using an average of seven seconds for each stop and seven stops per mile the resulting theoretical speed for the two-motor car becomes 11.43 miles per hour, while for the four-motor car it is 12.92 miles per hour. The distribution of running time and the variation for the two types of cars is shown in Table I.

An analysis of the operating costs was made for each type of car, and a summary of the operating costs and fixed charges is given in Table II. The energy cost increased nearly 39 percent. Although the cost of the four-motor car is greater than that of the two-motor car, the reduction in cars needed compensates to such

TABLE II—SUMMARY OF ANNUAL OPERATING AND FIXED CHARGES OF TWO AND FOUR-MOTOR CARS
(Crawford Ave. Line)

| | Two-Motor Cars | Four-Motor Cars |
|---|---|---|
| Trainmen's Wages | $ 529 097 | $ 465 353 |
| Cost of Energy at the Car | 116 129 | 161 495 |
| Cost of Motor Maintenance | 14 742 | 16 517 |
| Cost of Car Cleaning | 15 603 | 14 220 |
| Interest Charges on Cars | 65 175 | 66 600 |
| Interest Charge on Car House Investment | 15 800 | 14 400 |
| Totals | $ 756 546 | $ 739 585 |
| Net Annual Saving with Four Motor Cars | | 17 961 |

an extent that the interest charge on the cars and the housing is substantially the same. The only two items having material differences are the trainmen's wages and the cost of energy. The net result at the Chicago rates shows a saving for the four-motor car of about 2.5 percent. Of course, such a saving is not important in itself, but the fact that it is a saving is highly important when one considers the increased speed available, the increased dependability of service in all kinds of weather and, therefore, the increased sales value to the public. When conditions create slippery rails, two-motor cars cannot maintain scheduled operation with the same regularity as can four-motor equipment.

The net result of four-motor car operation on such a line would be to produce a greater gross revenue and

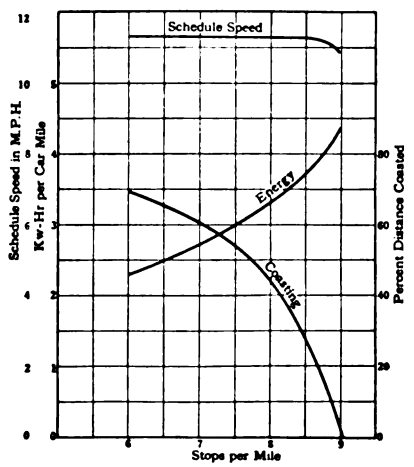


FIG. 2—INFLUENCE OF STOPS ON CAR PERFORMANCE
The car characteristics being the same as for Fig. 1.

a greater net revenue. A further direct and measurable asset results from the greater speed because other traffic has more respect for a street car that is powerful, operates with an apparent purpose, and which asserts its importance because of its ability to move faster than other street traffic.

The relation between the number of stops per mile and the energy consumption for a uniform schedule speed is shown in Fig. 2. It illustrates clearly how

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rapidly the energy use increases on the busier lines.

A recent survey of the Irving Park line in Chicago, which has an average schedule speed of 12.37 miles per hour and is 7.21 miles long, shows this line to make six stops per mile as an average. The cars have four 40 hp motors and weigh 45 800 lbs.

On the entire Chicago system of 1010 track miles there are 8574 passenger stops and 612 points requiring double safety stops at railroad crossings and bridges. The average number of stops made per mile of operation is not of record, but the speed attained is 11.30 miles per hour, and it is hoped to increase this rate, although it will move very slowly and probably will never pass 12 miles per hour. Since many of the older and smaller cars are due for replacement, as soon as the franchise arrangements have been settled, there will then be one opportunity for a sharp increase in speed.

Speed, however, can be increased materially, in many cities, without a change in equipment. It is not the capacity of the car motors to create speed that is the sole or even controlling influence in determining the speed of operation. Much higher speed than that existing can be attained if there is careful elimination of delays. The effect of decreasing the number of stops has already been mentioned. Public education can result in eliminating many wasteful stops in the interest of the greatest good to the greatest number.

The next most important factor is the training of the crews and of the supervisory force. The train crews are well paid and should be competent men who are susceptible of education to a point where they will do their work in a most effective manner, giving courteous service with safe and speedy operation, because of constant attention to the details involved in getting the cars over the road quickly. This requires careful training in many little things, such as uniformity in making stops, smoothness of operation, speed in opening or closing the doors, passing the bell, getting under way, skill in working through traffic, maintaining a uniform headway, operating exactly on schedule time, and in so pleasing the passengers that they will in turn respond to the apparent business-like activity of the crew.

The management in turn must do its part more thoroughly by building schedules fitted to the possibilities of the equipment and to the riding. Running times should fit the operation which can be developed at the various hours of the day. Supervision should be carefully adequate, competent and sympathetic, and should check the operation as to accuracy, and assist the train crews to maintain accuracy in spite of the interferences from traffic delays. The management must arrange so that the track is in condition to encourage and justify rapid movement, switches are safe, curves will not cause derailment, special work other than facing switches may be traversed at a reasonably high speed. It must be sure that the overhead wiring is in good condition, safety-zones are installed at busy points, front-end loaders are placed where necessary, supervisors are placed at points of greatest traffic congestion to assist the motormen in getting through, the police department is in sympathy with the prompt movement of cars, the traffic control is wisely placed and effectively operated, and the cars are so operated as to permit the maximum speed in loading and unloading. Then, too, the management can be active to see that paving outside the track is improved to permit vehicles to operate alongside the railway cars, streets are widened as needed, unnecessary obstructions due to parking at congested bottle-necks are removed, also that cab stands are taken from points where they create confusion, and that generally appropriate regulations of traffic and street control are adopted to permit all vehicles as well as the street cars to move with greater freedom.

Developing greater street freedom is a large and complicated job, but it is an important obligation upon the railway managements. If the railroad has its own house in order as to the effectiveness of the employees, the schedule arrangement, the supervision, the operating methods and the routings of its cars so as to provide the minimum of avoidable interferences with other traffic, then the management can legitimately press the city government for the improvement of street and traffic control to permit more rapid movement.

New equipment does not alone provide the answer. Of course, modern cars of the better designs would help tremendously if of high motor power capacity, but it is the endless attention to all the little details of operation that really produces the high average speed for which all railroads should be seeking.

Managements can improve their operating conditions tremendously, if they are willing to do the necessary detail work, but it does require much careful, conscientious and continuous struggle.

If high speed could be obtained by buying something which would, in itself, produce the answer, all railways would have it. Since it is a problem of detailed obligation for all parts of the organization, sponsored most intimately by the management, it is more difficult to obtain generally. Many railways are working in this direction, while others will, undoubtedly, soon be forced into a more aggressive attitude.

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# Fundamentals of Blow-Out Structures

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Westinghouse Electric & Mfg. Co.

IT is well recognized that series traction motors present a difficult switching problem due to the relatively high inductive effect of the motors themselves, and also the inductance of heavy capacity feeders and third-rail networks with rapidly changing loads. Recent years have seen a very great increase in the power capacity available on electric traction lines, particularly in 600 volt and 1500 volt direct-current service, and the switching duty increases in severity with the available capacity. Electric locomotives and multiple-unit trains require switching equipment not only for starting and accelerating, but also for overload and short-circuit protection, all combined in the same control equipment.

## CHARACTERISTICS OF THE ARC*

When current carrying members are separated under load conditions which establish a potential of 50 volts or more between the contacts, a stable arc may be established wherein ionization takes place. The current is carried to the cathode by an arc stream of positive ions and creates a hot cathode spot estimated to be at a temperature of 2000 degrees C. for copper contacts. The intensity and duration of this arc depends on the distance and speed of separation, the voltage and the current to be broken and the adequacy of artificial means provided for stretching and cooling the arc stream. When, due to the influence of any or all of these, the arc resistance is increased so that the voltage drop in the arc approaches within 50 volts or less of the line voltage, current ceases to flow, the arc is extinguished and the circuit is completely broken.

For practical conditions, currents of 100 amperes or more at voltages above 50 volts, which must be broken repeatedly, require some artificial means for extinguishing the arc. In some classes of commercial apparatus, it is not practicable to separate contacts more than one inch, and this distance is not sufficient for anything but light duty unless some auxiliary blowout effect is produced.

Cooling is accomplished by the large mass and resultant thermal capacity of anode and cathode; also by the exposure of the arc to air and to large surfaces of insulating material. Stretching is accomplished; first, by quick separation of the terminals; second, by self-induced horn-gap expulsion action of diverging terminals, and third, by magnetic blowout action from a suitable magnetic field acting on the arc stream as a moving conductor.

*For reference see:—"Characteristics of the Electric Arc" by Prof. K. T. Compton, also papers by Dr. J. Slepian in *Franklin Institute Journal* Vol. 201 1926, and *Physical Review*, Vol. 27 1926.

Enforced arc rupturing in a magnetic field reduces the total time of the duration of the arc and minimizes the loss of material carried away by the vaporizing action of the heat. It also creates an explosive effect due to the high expansion rate of the gases, and adequate disposition must be provided for these gases in the form of an insulating chamber or an arc chute.

The rapidly diminishing current in the arc is accompanied by an increasing arc voltage, the magnitude of the latter sometimes reaching several times that of the line voltage, depending on whether the load is inductive or non-inductive, and upon the stored energy of the supply feeder system. The proportions of the switch contacts, arc box and strength of the magnetic blowout combine to establish an inherent time constant of the system as a whole.

While the arc is being forcibly elongated and the current decreased, the over-voltage surge may establish a second arc between the contacts, thus again increasing the current by having two arc streams in parallel. The second may be followed by a third, and an oscillation set up consisting of a succession of parallel arcs and a rapid fluctuation of arc voltage, resulting in excessive volumes of gas and loss of contact material. This phenomena of reëstablishment constitutes one of the major problems in switch design. It can be prevented or minimized by suitable speed of separation between contacts, and prompt disposal of low resistance gases which may otherwise encourage the breakdown of line voltage between the contacts after they have separated. In cases of high voltages, such as 1500 or 3000 volts, the introduction of two breaks in series establishes two arcs and greatly reduces the probability of reëstablishment. In order to stabilize the distribution between the two series arcs it is sometimes advantageous to connect a relatively low resistance in shunt with one of the switches. This establishes a definite potential across the shunted switch and prevents localizing of the entire voltage peak across either pair of contacts. This action is somewhat similar to that of a condenser-type terminal bushing in distributing potentials over several gaps.

The fundamental problem of switch design is to establish proportions which will interrupt both normal and abnormal loads with a minimum of contact and arc box destruction, and without building up extremely high arc voltages which may damage other apparatus connected to the system.

## SWITCH STRUCTURES

Inasmuch as all traction equipments are operated on circuits with grounded negative, the switching must

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be done on the positive side only. Therefore, in providing gas space and insulated structures, the containers, supports and adjacent metal parts must be considered as one side of the line. Gases must not be permitted to drift undirected, but must be confined to spaces where no direct path to ground can be established. It is with this condition in view that universal practice has established that traction switches direct their arcs horizontally into an insulated chamber, rather than vertically where clearances would be limited and the grounded structures difficult to avoid.

Four distinct forms of blowout structures are in regular use, each one having its particular field of application.

*A*—Alternate switches and series coils forming a permanent group assembly with a continuous magnetic circuit passing longitudinally from end to end.

*B*—A single series coil mounted in the vertical plane of the contact, each switch being an independent unit.

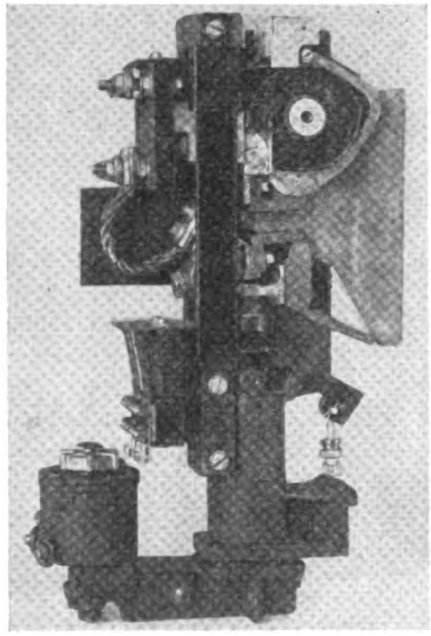
*C*—Similar to *B* in that each switch is independent but with two series coils one on each leg of a magnetic yoke.

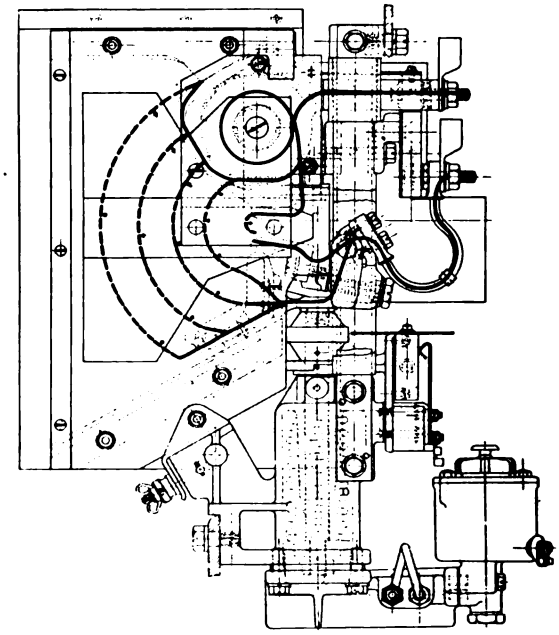
*D*—A magnetic yoke without a series coil, the flux being induced by the location of the magnetic material with reference to the current carrying members of the switch.

*Class A*—The group construction of switches has a limited but very definite application where the number of switches required is fixed and of sufficient quantity to justify the cast frame and panel construction. The switch units and blowout coils are assembled in regular order beneath a horizontal panel of magnetic material, with back cross connections in a compartment above the panel. A series blowout coil between each switch unit, together with a set of pole pieces for each coil, sets up a magnetic field which is continuous from one end plate to the other, passing across each set of switch jaws and having a return magnetic circuit through the horizontal base plate. This construction is applicable only where it is convenient to connect all of the coils in a single circuit so that they are all active and all receive the same number of ampere turns. If this is not done, an inactive coil will cause distortion of the magnetic field, resulting in imperfect blowout of the adjacent switch, and probably side burning in the arc chute. This construction has the mechanical advantage of a separate compartment for all of the cross-connections; and any one blowout coil or switching mechanism is easily removable without disturbing other parts of the assembly. It is disadvantageous in that there is considerable leakage of flux from the edges of the poles directly up to the base plate, thus upsetting the ideal condition of having straight lines of flux across the arc box. Such distortion of the magnetic field causes localized swirling of hot gases and unnecessary burning.

*Class B*—Figs. 1 to 6 illustrate switch units which utilize the single-coil blowout structure, and these views are in sufficient detail to indicate the relative location of contacts, blowout coils and magnetic-pole pieces. Substantial metal arc members or horns are located close to the tips of the contacts, to draw the arc away from the removable contact itself and on to the more massive permanent structure, which has sufficient thermal capacity to be unaffected by normal arcing duty. It has been found that the active surface of arcing members should be either concave or flat but not convex. The arc stream tends to leave a metal surface at right angles to the surface tangent. Convex surfaces, therefore, have a tendency to drive the arc sidewise into the corner of the arc box.

Assuming a uniform distribution of flux between the pole pieces, all points of the arc stream are driven outward at approximately a uniform rate. The ideal condition would be to have the arc horns long enough





FIGS. 1 & 2—ASSEMBLY AND SECTIONAL VIEWS OF A 600 VOLT UNIT WITH CLASS *B* BLOWOUT

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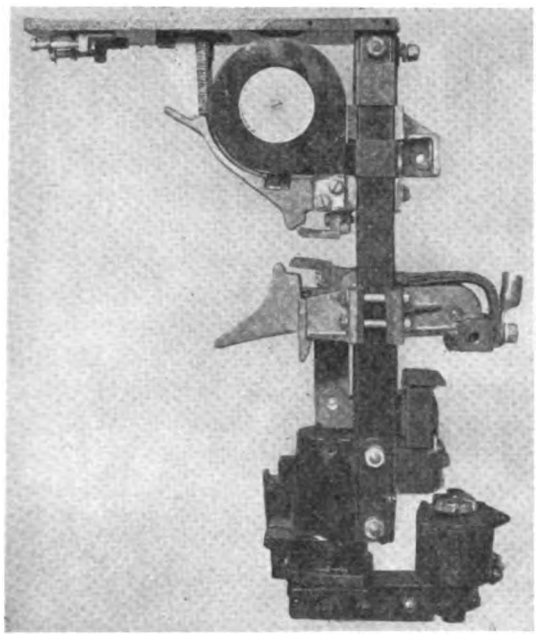
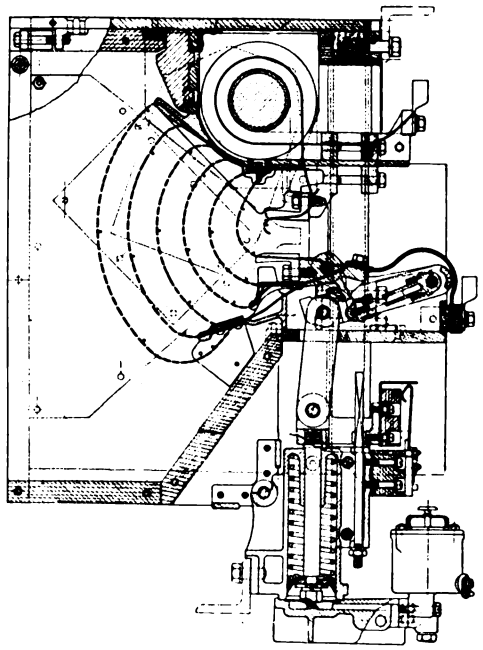
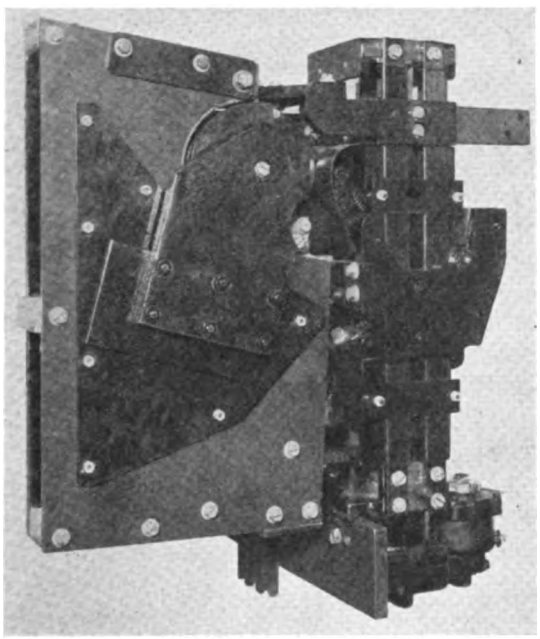
so that the arc terminals will continue to move through the entire period of arc duration. The hot spot would, therefore, be moving and would not be confined to any one place on the horn long enough to melt away any appreciable amount of metal. In practice it is sufficient to provide arc horn lengths to take care of normal arc loads, with the expectation that in case of heavy overloads there will be abnormal burning at the extreme ends of the arcing members. The great variation in arcing duty to which any individual unit might be subjected covers a range from 25 percent of the continuous rating up to possibly 100 times this rating. The commercial design must, therefore, be a compromise which experience indicates will give a reasonable life for the parts affected by the arc.

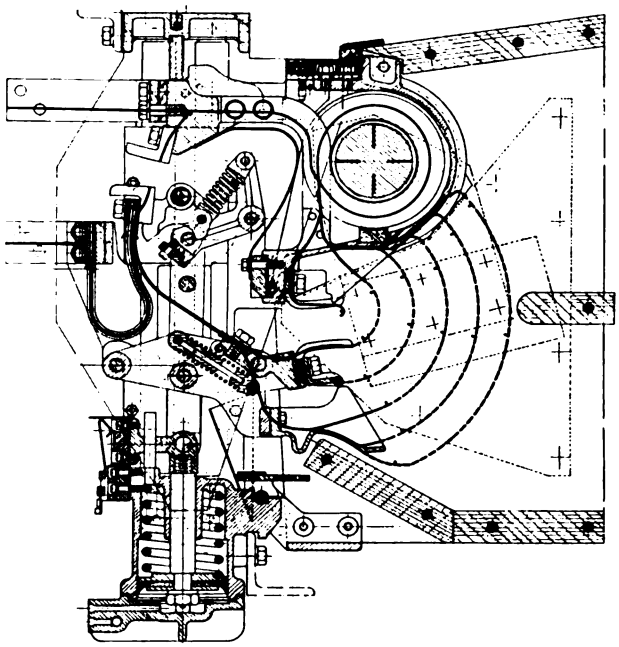
*Class C*—Figs. 7 and 8 illustrate a pneumatic unit using the double-coil structure. As compared with the single-coil structure this arrangement lends itself to a reduction in the height of the unit, although the width is somewhat increased. It is also possible to use a flat-wound coil instead of an edge-wound coil, and thereby establish the necessary amount of flux with a reduced number of ampere-turns. In the edge-wound structure there is necessarily leakage from that portion of the coil turns outside of the magnetic yoke. A large core is, therefore, necessary in order to prevent





FIGS. 3 & 4—A 1500 AND 3000 VOLT UNIT USING CLASS *B* BLOWOUT WITH WIDE ARC BOX OPENING





FIGS. 5 & 6— A CLASS *B* BLOWOUT WITH A 2500 AMPERE UNIT
The coil and arcing contacts shunt the main contacts, which separate first as the switch opens.

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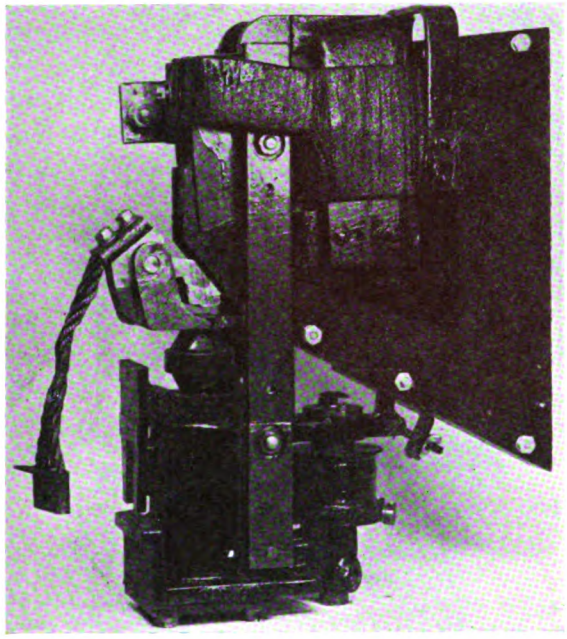
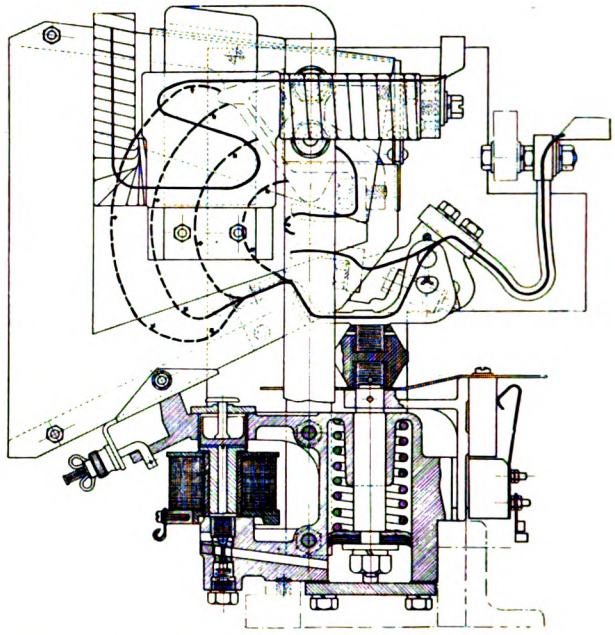
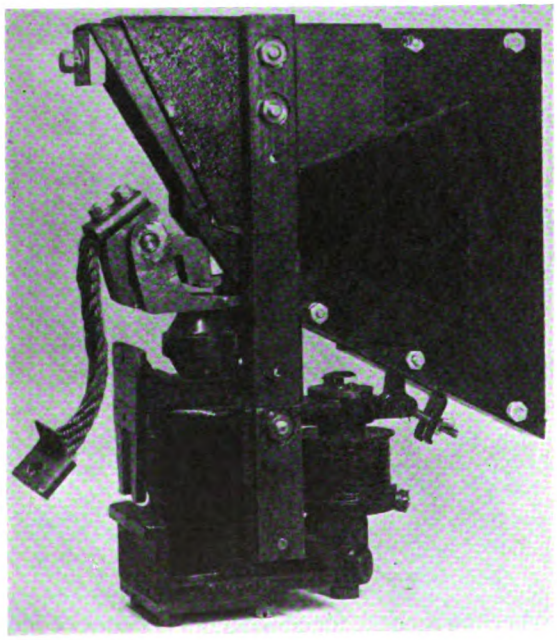
premature saturation on overloads. In the case of the double-coil construction, leakage is reduced to a point where for practical purposes it can be disregarded. Aside from the possibility of height reduction, greater magnetic efficiency is secured because of the reduced leakage. The natural leakage path is directly across the main gap, whereas in class *B* there is an excess of leakage from end to end of the core, entirely outside of the arc box. The continuous yoke also eliminates the imperfect joint at the ends of the coil core, and so reduces the total reluctance.





FIGS. 7 & 8—A PNEUMATIC UNIT USING CLASS *C* BLOWOUT



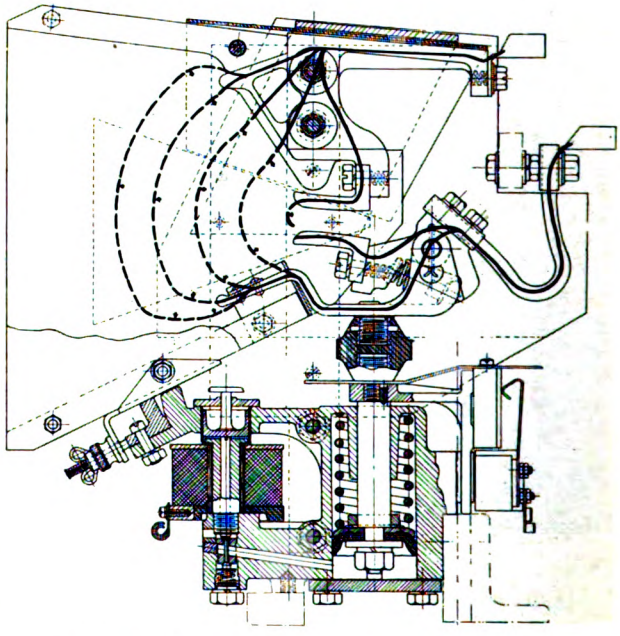


FIG. 9 & 10—A UNIT USING A CLASS *D* BLOWOUT
A companion design with class *C* blowout is shown in Figs. 7 and 8.

*Class D*—It is only recently that the coil-less blowout principle has been applied to switches, although it has been the basis of ribbon fuse box design for a long period. The fuse element is suspended in a loop, and the flux resulting from this single turn is intensified by a magnetic hoop surrounding the arcing chamber. While the resultant flux density is very low, fuses blow only at high currents, and at infrequent intervals, so the resultant slow rupturing rate does no permanent damage to the horns or box, and such devices are entirely successful. Contactors used for shunting starting resistors, and similar duty, where the arcing is at low voltages and of infrequent occurrence, are now successfully produced on the same principle. Such an arrangement is shown in Figs. 9 and 10. The magnetic yoke is nearly the same as that used in Class *C*, but the top portion is flattened out and the incoming

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current is carried inside the loop, in passing to the upper arc horn. The result is a single-turn blowout sufficient for light duty. By properly coordinating such switches with those of the heavy-duty class, the space and weight factors of a complete motor control equipment can be improved. All operating and renewable parts, including arc boxes are uniform throughout, the assembly being the companion of that shown in Figs. 7 and 8.

### THE ARC PATH

The line drawings used to illustrate the four classes of blowout structure have been supplemented by heavy lines indicating the current path, the successive positions of the arc stream being shown by the broken portion of the line. It is reasonable to assume (and this is confirmed by photographic observations) that in a uniform field all portions of the arc stream move at a uniform rate and in an ever widening circle. Arrows indicate the direction of movement for each sector as being at right angles to the current in the arc stream. Whenever current and voltage combine to prolong the arc until after it reaches the ends of the horns, the arc terminal passes around the end of the horn and the direction of blowout is reversed. Such a condition is easily controlled at the top or stationary horn by making the arc box gas tight. However, at the lower or moving horn steps must be taken to protect the working parts of the switch, either by an overlapping stationary horn as in Fig. 3, or a small neutralizing pole of the *D* class, located to protect the bottom of the moving horn, as in Figs. 1 and 2.

The width of arc box is determined by the size of contacts to be used, and is made as narrow as clearances will permit, so as to secure full advantage of the turns in the blowout coil. Pole areas are made to cover the contacts and a portion of both horns, since an arc terminal outside the uniform field of parallel lines wavers from side to side and starts localized burning in the arc-box linings.

In all cases the arc box is made as open, vertically, as mechanical clearances will permit. The greater the angle subtended by the arc stream sector, the more readily the arc is stretched to the point of complete rupture. It is for this reason that circuit breakers of the high-speed station type are fitted with arc openings of 180 degrees or more. The horizontal dimension of poles must be at least half of the height; and greater if the height is unduly restricted.

*(To be Continued)*

# Armature Coils Used to Maintain Railway Motors

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THE armature coils used in modern railway motors are vastly different in construction, kind of insulation and type of conductor from those used in early motors. The evolution of the railway motor armature coil is an important and interesting subject, as it covers the details of construction and insulation, which have a decided effect on the useful life of the winding and the total time required to wind, connect and band the armature.

Four methods of fabricating railway motor armature coils are indicated in Table I:—(1) Winding to final shape on a mould. This applies to wire wound coils. (2) Winding on a shuttle in loop form, and

TABLE II—TYPES OF INSULATION

| Classification No. | Name Based on Temperature | Conductor Insulation | Material Used for Wrappers | Material Used for Sleeving and Final Taping |
|---|---|---|---|---|
| 1 | Normal | Cotton | Treated cloth | Cotton |
| 2 | Semi-high | Cotton | Mica and fishpaper | Cotton |
| 3 | High | Asbestos | Mica and fishpaper | Cotton |
| 4 | Full class B | Asbestos | Mica and fishpaper | Asbestos |
| 5 | Normal | Cotton | Mica and fishpaper | Cotton |
| 6 | High | Mica tape | Mica and fishpaper | Cotton |
| 7 | Full class B | Mica tape | Mica and fishpaper | Asbestos |

Note.—Insulation numbers 1-2-3-4 apply to wire or ribbon. Wound coils and numbers 5-6-7 apply to bare copper strap coils. Insulations 1-2-5 are A. I. E. E. Class A. Insulations 3-6 are A. I. E. E. Class B modified. Insulations 4-7 are A. I. E. E. Class B.

TABLE I—TYPES OF RAILWAY MOTOR ARMATURE COILS

| Classification Letter | Figure No. | Name Based on Shape of Coil | One or Two Pieces | Conductor | Method of Winding | | | Types of Insulation |
|---|---|---|---|---|---|---|---|---|
| | | | | | How Shaped | How Wound | Winding Coil | |
| D | 1 | Elliptical | One | Wire | Mould | Single | Paper | 1 |
| E | 2 | Diamond | One | Wire | Mould | Single | Paper | 1-2-3-4 |
| F | 2 | Diamond | One | Wire | Mould | Complete | None | 1-2-3-4 |
| G | 3 | Diamond | One | Wire or Ribbon | Puller | Complete | None | 1-2-3-4 |
| H | 4 | Diamond | One | Strap | Former | Complete | None | 5-6-7 |
| K | 5 | Diamond | Two | Strap | Former | Complete | None | 5-6-7 |
| M | 6 | Short Type | One | Wire | Mould | Single | Paper | 1-2-3-4 |
| N | 6 | Short Type | One | Wire | Mould | Complete | None | 1-2-3-4 |
| P | 7 | Drop Type | One | Wire | Mould | Complete | None | 1-2-3-4 |
| S | 8 | Double Loop | One | Ribbon | Former | Complete | None | 2-3-4 |

Note—Wire is any metal of round or square cross-section received at the point of application coiled on reels, bare or insulated. Ribbon is any metal of rectangular cross-section received at the point of application coiled on reels, bare or insulated. Strap is any metal of rectangular cross-section received at the point of application coiled, bare, i.e., bare copper strap.

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then pulling to final shape in an adjustable pulling machine or shuttle puller. This applies to wire and ribbon coils. (3) Forming to final shape on wood or iron formers. This covers bare copper strap coils. (4) Winding to special intermediate shape on a special shuttle and forming the final shape on a wood or iron former. This method is termed shuttle forming, and

FIG. 1—ELLIPTICAL TYPE OR *D* COIL
Showing the two sizes of coils used.

applies to ribbon coils. These four major methods are subdivided into smaller groups which lead to the types of coils given in the table and illustrated in Figs. 1-9 inclusive.

Before discussing the practical construction details of the principle types of coils, a definition of the common standard terms used in coil work will be given.

*Strand*—any single bar, strap, wire or ribbon capable of carrying current.

*Conductor*—one or more strands adjacent to one another and electrically in parallel.

*Turn*—one conductor making one complete loop electrically around a magnetic circuit.

*Single Coils*—the unit that forms the electrical circuit between any two commutator bars.

*Armature Coil*—a complete mechanical unit ready to be installed on the armature.

*Two Piece or Half Coils*—an armature coil made in two separate pieces and connected together with clips at one end after installing on armature, as in Fig. 5.

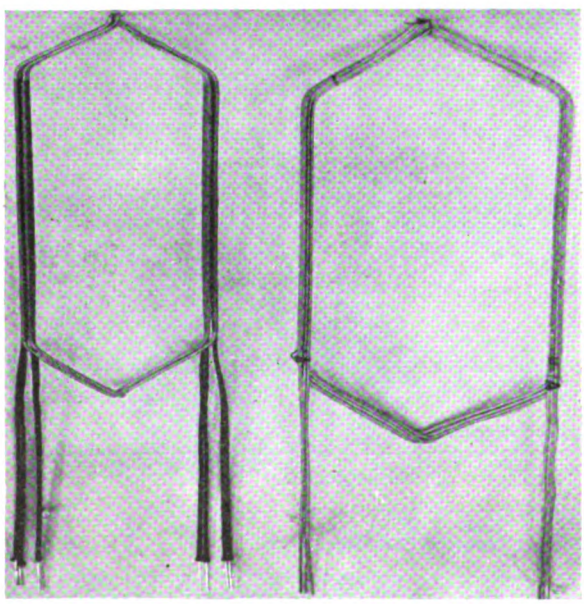

FIG. 2—DIAMOND, MOULD WOUND COILS, TYPES *F* (LEFT) AND *E* (RIGHT)

*One Piece Coil*—a mechanical unit made complete without connections or separate parts, as in Figs. 4 and 9.

*Left Hand Coil*—hold coil with leads towards you and in the position it would assume when in the armature slots, then if the top half of the coil, i.e., part nearest air-gap is to the left then coil is left hand. With left hand coils, the armature should be wound with the commutator on the winder's left, and the top half of the coils pushed away from the winder; this is the most efficient position for placing and shaping the coils and for laying the bottom leads.

*Right Hand Coils*—hold as above, and if the top half of coil is on the right, the coil is right hand. For right hand coils, the commutator should be on the winder's right.

Fig. 9 illustrates the above terms as it is a left hand armature coil, one piece, composed of five single coils, and each single coil conductor consists of two strands in parallel.

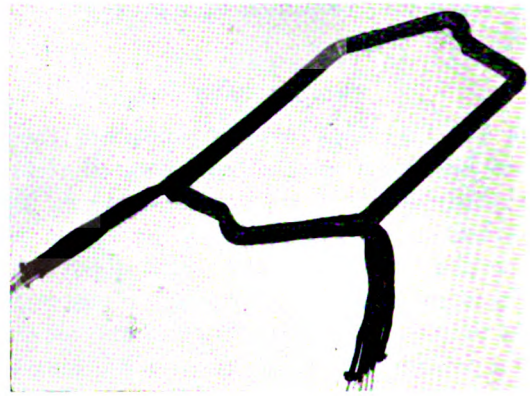

FIG. 3—THE DIAMOND SHAPE SHUTTLE PULLED COIL, TYPE *G*

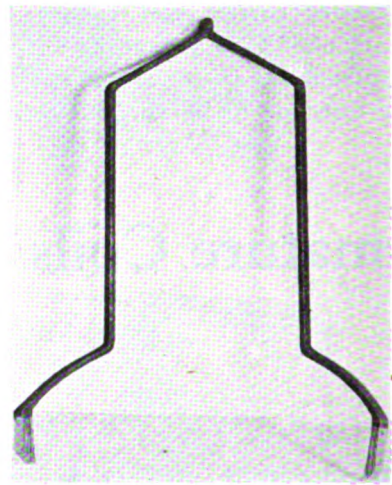

FIG. 4—THE ONE PIECE DIAMOND, STRAP COPPER COIL, TYPE *H*
This is a one turn coil for a wave winding.

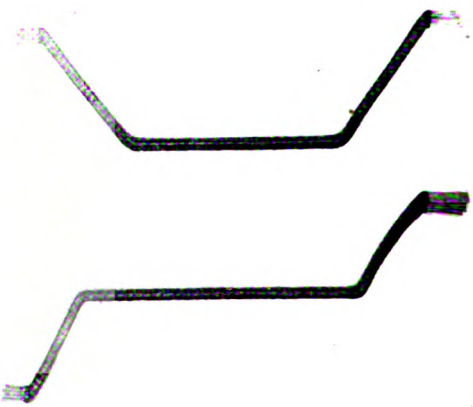

FIG. 5—TWO PIECE DIAMOND SHAPE, STRAP COPPER COILS, TYPE *K*
Showing both a wave and lap winding coil. For lap windings both the front ends bend in towards the center of the coil; for wave windings the front ends bend away from the center of the coil.

## CONSTRUCTION OF COILS

The first step in the construction of armature coils is to work the raw material, as wire, ribbon or strap,

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into a single or complete coil, and the most common method consists of winding wire onto a wood or iron mould, thus the term mould wound. The moulds can be built so that one single coil, or a complete coil can be wound. This explains the reasons for the term

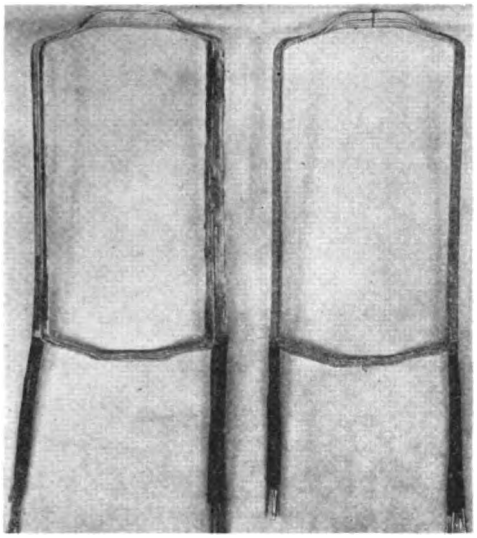

FIG. 6—SHORT-TYPE MOULD-WOUND COILS, TYPES *N* (LEFT) AND *M* (RIGHT)

wound single, as in coil types *D*, *E*, and *M* of Figs. 1, 2, and 6, or the term wound complete as in coil types *F*, *N*, and *P* of Figs. 2, 6, and 7.

Winding coils on a mould is one of the most exact and expensive methods. The coils can be wound to exact and intricate shapes, and each succeeding coil is a duplicate of the preceding ones. The method is expensive, as the first cost of the mould is high. It also requires constant maintenance to insure correct coils and, when not in use, moulds must be recorded and stored, thus taking up valuable manufacturing space.

However, the types of armature coils used in railway work are of a nature that do not permit the use of any other mediums than moulds or formers, with the exception of a few small coils that can be made on adjustable pulling machines.

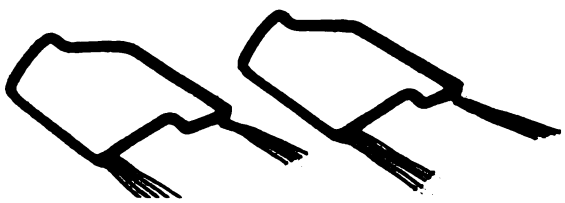

FIG. 7—DROP-TYPE MOULD-WOUND COILS, TYPE *P*

In general, there are two separate and distinct methods of winding coils on a mould, and under each classification there are various systems employed to obtain the finished coils, but there are a number of fixed rules that pertain to both the wound-single or wound-complete method.

All wound-single coils are built up with the turns depth-wise in the slot, i.e., with the coil in the armature slot the succeeding turns are one above the other. This applies to coil types *D*, *E*, and *M*, Figs. 1, 2, and 6. With wound-complete coils, the turns are built up depthwise in one type, and widthwise, i.e., across the slot, in another type, e.g., coil types *F* and *N*, Figs. 2 and 6 are built up depthwise, while coil-type *P*, Fig. 7 is built up widthwise. Thus the rule is that a mould-wound coil, with turns built up widthwise in the slot can only be wound complete, whereas coils wound on a mould depthwise can be either wound single or complete.

Elliptical, diamond, or short-type coils, wound single or complete, can be wound by starting on top or starting on the bottom. The top is that portion of

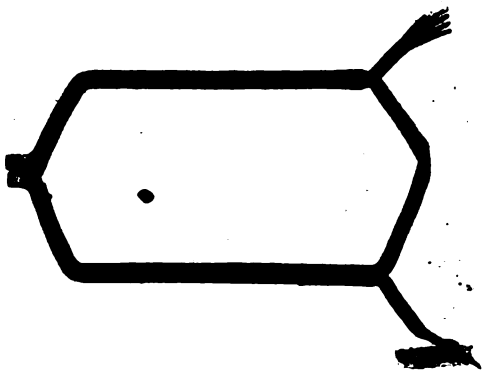

FIG. 8—DOUBLE-LOOP SHUTTLE-FORMED COIL, TYPE *S*

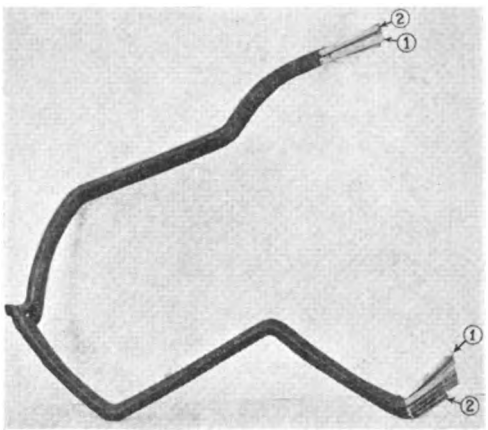


FIG. 9—COMBINATION OF DOUBLE-LOOP AND ONE-PIECE STRAP-COPPER COIL

Each conductor is divided into two parts. This is termed stranding, which reduces the copper losses, as eddy currents are thereby reduced. Also the double loop at the rear end is used in this case to transpose the strands, which further reduce the eddy current losses. The small numbers 1 and 2 indicate how the position of the strands in the solid section are transposed. With straight loop coil, strands 1 and 2 at the left of Fig. 9 would be interchanged; but strands 1 would occupy the position in the top and bottom of the slots and strands 2 would be in the center of the slot. In other words the arrangement would be 1-2-2-1, whereas by transposing the arrangement becomes 1-2-1-2.

the coil nearest the air-gap when the armature is wound. Then with a coil started on top, the leads will be brought out from the bottom of the coil. With a start on the bottom coil, the leads will be brought out from the top of the coil. Thus there are two methods of starting the coils, resulting in the leads being brought

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out from the coil in two different positions. This rule can be condensed, as leads on top start on the bottom, as in Fig. 6; or leads on the bottom, start on top, as in Figs. 1 and 2.

These last two rules are important, as the coil man thinks in terms of starting or finishing leads, whereas the armature winder uses the terms top and bottom

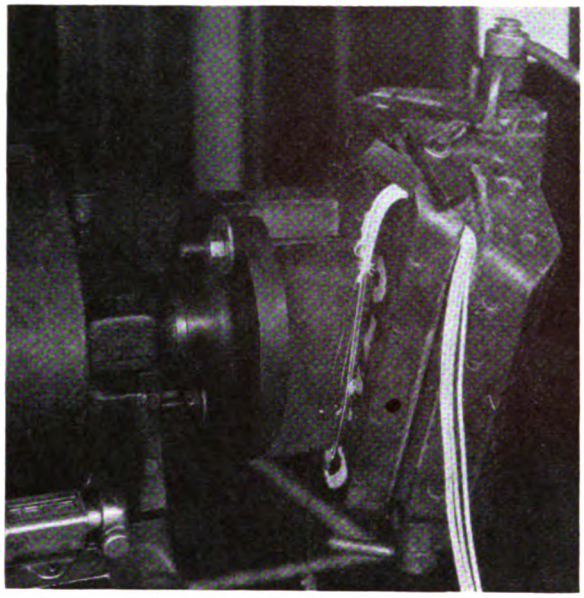

FIG. 10—STARTING A COIL ON A FORMER

leads. Thus the type of coil and method of bringing out the leads must be known before both men can fully understand one another.

It is interesting to note that the majority of diamond-shaped, mould-wound coils have the leads

FIG. 11—SKINNING THE INSULATION FROM THE LEADS IN SUCH A MANNER AS TO AVOID NICKING THE COPPER

brought off the bottom; and that the short-type coils have the leads brought off the top. This condition arises from the practical factors that mould construction, winding, and removing the coils from the mould are greatly facilitated.

Regarding the winding and connecting of armatures, the coils with leads brought off the top have a slight advantage in that the coil can be placed in the machine and the leads bent to better advantage. With leads on the bottom, the top leads must be bent before inserting the coils, often necessitating a second bend;

FIG. 12—WINDING A PULLER COIL ON A SHUTTLE

but this is off-set by the fact that the bottom leads lie better when brought off the bottom, which is an advantage on small diameter armatures.

The drop-type coil, Fig. 7, is wound with the turns built up widthwise in the slot, and has the bottom leads fanned out and brought off the bottom of the coil. The top leads are brought off the side of the coil. They are bent up against the coil, fanned out and tied in place, resulting in a coil that can be installed without the winder bending the leads.

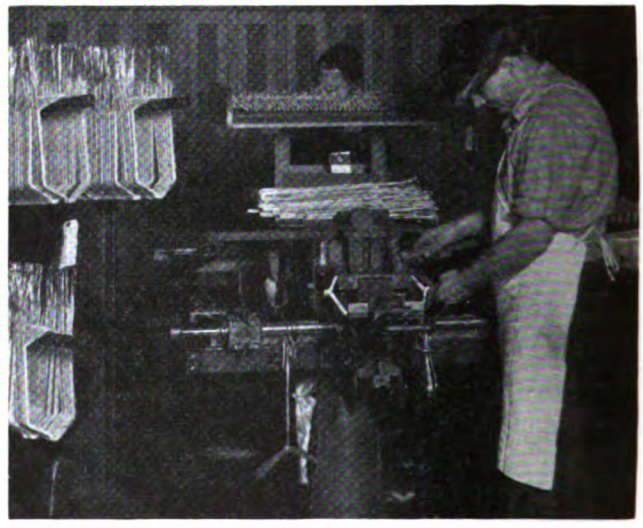

FIG. 13—PULLING TYPE *G* COILS INTO FINAL SHAPE
With a conveniently arranged truck at the left to receive the finished coils.

The start of a drop-type coil is shown in Fig. 10. This is a start-on-bottom coil with leads on bottom and top. Note how the bottom leads are fanned out and are part of the front diamond section of the coil.

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Mould-wound, single or complete coils can be wound without paper cells, or wound in paper cells, wound without sleeving or the winder can apply the sleeving. This sleeving is caught under the paper cell. The advantage of this method is a stiffer coil, handling and operations reduced, with sleeving and leads securely fastened.

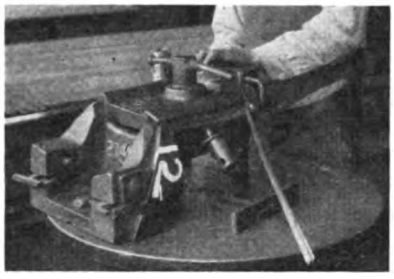

FIG. 14—FORMING BARE STRAP COILS, TYPE *H*

The mould-wound complete coils are generally wound without sleeving or cells. These are placed in subsequent operations. Fig. 11 shows the winder skinning the cotton covering from the leads with scissors.

The type *G* shuttle-puller coils are first wound into loops on a shuttle similar to the one shown in Fig. 12. The coils then have shellacked strips inserted and pressed and pulled to shape as shown in Fig. 13. The coils in shuttle form and final shape can be seen in this picture. The method can be used only for the smaller railway coils and has the advantage of being flexible, as the tools are adjustable.

The leads of shuttle puller coils can be brought off the top, bottom or side, and the coils can be made left or right hand. To have leads on bottom, the coil is placed in the puller in shuttle form, with leads on bottom; reverse this for leads on top. For left hand

FIG. 15—FORMING THE FRONT DIAMOND POINT OF A TYPE *S* COILS
Showing the special shuttle and winding operation of the double-loop type *S* coil.

coils, the coils must be wound with starting lead brought out from the right-hand side of the shuttle, and in pulling the leads are on the operator's right as shown in Fig. 13. For left hand coils, start on right and have leads on right when pulling. For right hand coils, start on left and have leads on left when pulling.

Formed and shuttle-former coils are fabricated from bare copper strap or ribbon wire, double cotton, or asbestos covered; with formed coils, the copper is first cut into correct lengths. One piece coils are bent into loops or hair pins.

All cut straps of two-piece coils, and all straps of one piece coils, after bending are annealed in a furnace so constructed as to keep the flames from coming in contact with the copper. The coils are then acid cleaned to remove scale, etc. Next the coils are formed to their final shape on an individual iron former, a complete coil being formed at one time, as shown in Fig. 14. The leads are also formed and shaped to fit into the proper commutator bars.

Shuttle-former or type *S* coils require more handling and shaping. First the ribbon is cut into correct lengths and the wires grouped in bundles having as many wires as single coils per complete coil. These

FIG. 16—FINAL FORMING OF TYPE *S* COILS

bundles are kept free from twists and crosses by short lengths of micarta tubing. They are wound to intermediate shape on a special iron shuttle, shown in Fig. 15. The operators are shown making the roll loop at the front diamond point.

After winding into shuttle form, the cotton covering is repaired at all loops. Next the top lead has a special bend put in, and then the coils are formed to final shape on an individual iron former. The lead shaping and forming operations are shown in Fig. 16.

In winding or forming coils, the wire should not be handled any more than necessary, as excessive bending hardens the copper. The strap or wire should not be hit with metal hammers. In all cases, use fibre drifts and do a minimum of pounding. Use sufficient tension on the wire while winding to insure all coils being wound down against the mould and thus having the same shape.

*(To be Continued)*

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# Operating Problems of Interconnected Power Systems

**WM. R. HAMILTON**
System Operator,
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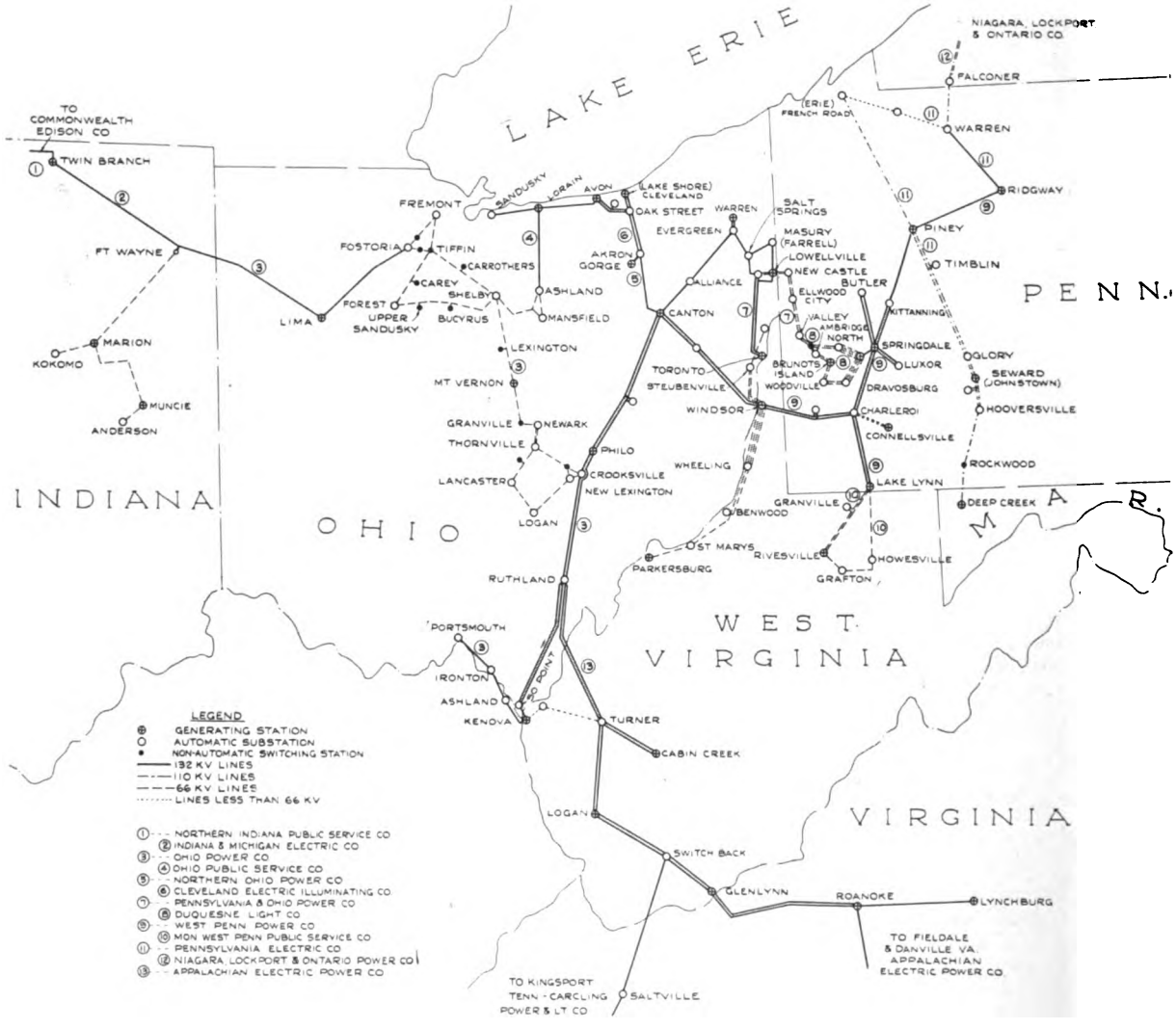
A GREAT deal has been learned during the past few years in studying interconnection problems through the medium of joint meetings of the operating organizations of different companies, committee meetings of the A. I. E. E. and N. E. L. A. and by actual tests among different companies. These tests, made under different load conditions, included the operation of long ties composed of strong and weak connections, and the closing of long transmission loops. At the numerous meetings among the operating departments of the various companies that were held, all the problems of parallel operation that arose were discussed and solved to the present satisfaction of all concerned.

Most of the larger power companies east of the Mississippi have experienced parallel operation with neighboring companies, and during the peak load of one day many of them operated in parallel as one mammoth interconnected system. This test showed that such operation is possible, but at this writing practical operation is limited by weak tie lines between certain companies. Additional transmission lines are being built or planned, which will make continuous parallel operation of all these companies a practical possibility and a desirable plan of operation.




THE TRANSMISSION SYSTEM OF THE WEST PENN POWER COMPANY AND ADJACENT INTERCONNECTED COMPANIES

The West Penn System has changed its operating practices because of the strengthening of its transmission system from that of an independently operated system which separated its generating stations upon the approach of storms, to that of a strongly-connected system which is interconnected to most of the adjacent companies at all times. Such operation with these companies now is favored as a continuous practice when close regulation of the interconnection can be obtained,

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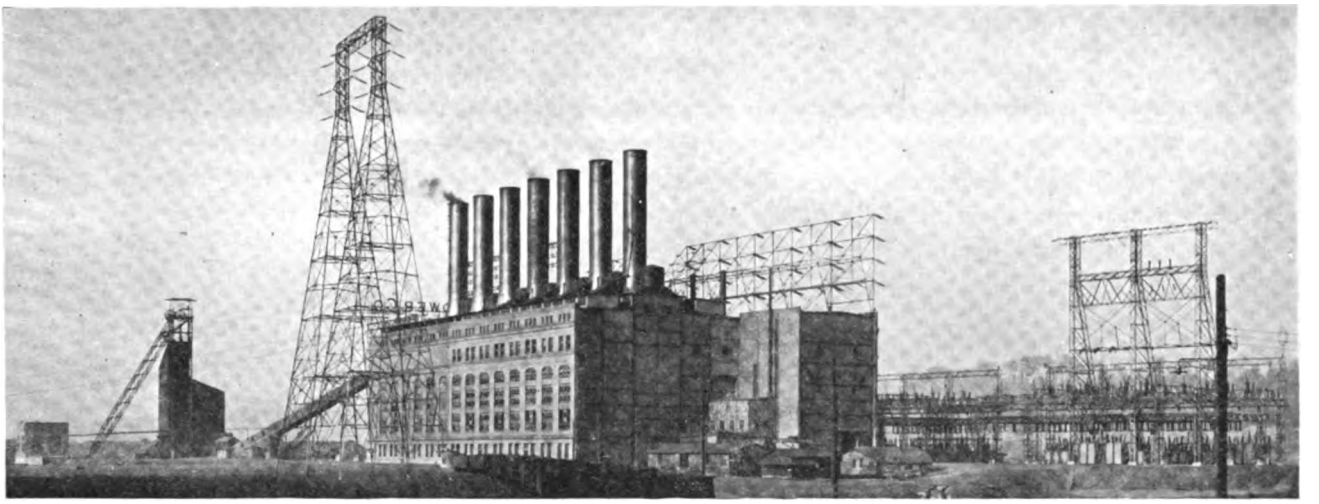


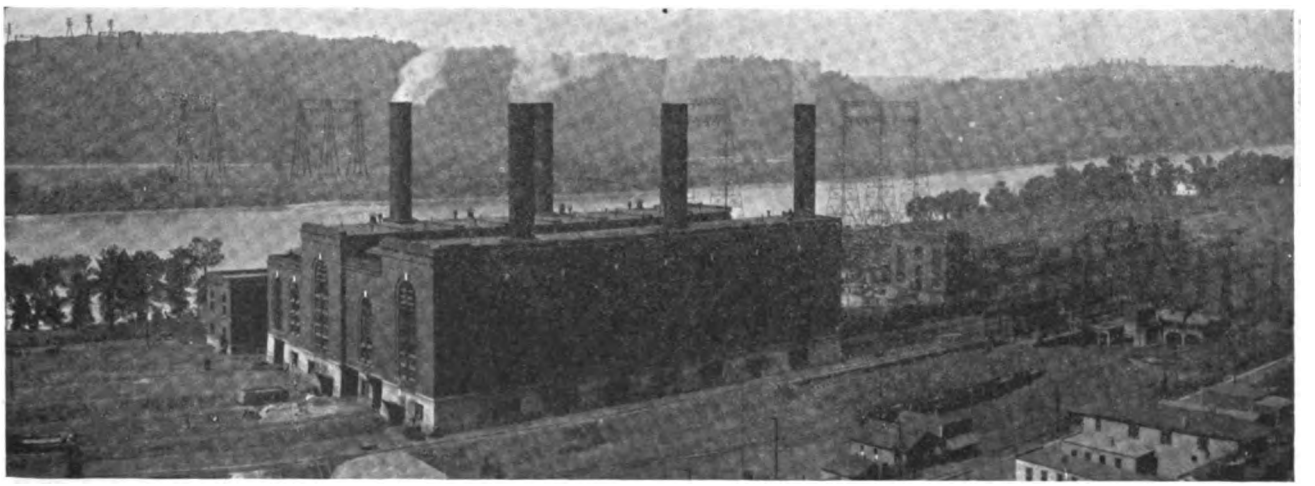
THE SPRINGDALE GENERATING STATION OF THE WEST PENN POWER COMPANY

This station, located on the Allegheny River, about twenty miles above Pittsburgh is one of the West Penn Power Company's largest stations. Its five steam turbine generators have a total capacity of 160 000 kv-a, at 80 percent power factor, generating at 11 000 volts and transmitting at 132 000 volts.

the benefits of such operation having been shown to the Company's organization.

Today, continuous parallel operation is maintained by the West Penn System with those companies to the west by means of the 132 kv transmission lines of this Company and the Ohio Power Company through the 180 000 kv-a Windsor power station in West Virginia, each company being connected to the Windsor generator bus through fixed ratio transformer banks. The Ohio Power Company operates in parallel with most of the companies in the state of Ohio either continuously or, as in the case of the Cleveland Illuminating Company, during the daily peak hours. Parallel operation often is established to the westward with the Commonwealth Edison Company in Chicago and southward with the Appalachian Power Company. The West Penn System maintains continuous parallel operation to the east with the Pennsylvania Electric Company of the Associated Gas & Electric Company System through a 15 000 kv-a autotransformer and automatic voltage regulator at the Piney hydroelectric station. The transformer and regulator ties together the 132 kv system of the West Penn and the 110 kv system of the Pennsylvania Electric. Both companies, through a jointly owned 132 kv transmission line, are interconnected to the 110 kv system of the Niagara, Lockport & Ontario Company. Regular parallel operation with the last mentioned company has not yet been established.

The Duquesne Light Company of Pittsburgh and the West Penn Power Company are interconnected by one 132 kv transmission line extending between their Colfax and Springdale stations, and at nine different points on the 25 kv systems. Parallel operation was maintained almost continuously for over a year over the 132 kv line and is established at any time upon the request of either company, either to maintain a satisfactory reserve, to exchange power or to transfer load on the 25 kv system. At Colfax station, the line connects to a 132/66 kv autotransformer and a remote



THE WINDSOR GENERATING STATION OF THE WEST PENN POWER CO. AND OHIO POWER CO.

This station is on the Ohio River about eleven miles above Wheeling and is jointly owned by the two power companies. It contains six steam driven generators, each generating 35 000 kv-a at 11 000 volts.

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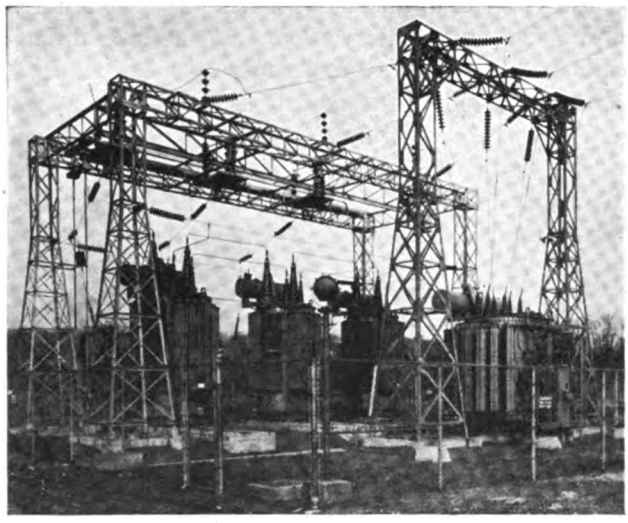
controlled tap-changing voltage regulator, and then to the station 66 kv bus.

Close regulation of the load among the interconnected companies proves to be the most difficult problem to solve satisfactorily, but the experience gained by time, during which many unexpected problems arose, taught each company the main problems of the others and all troubles were smoothed out quite easily.

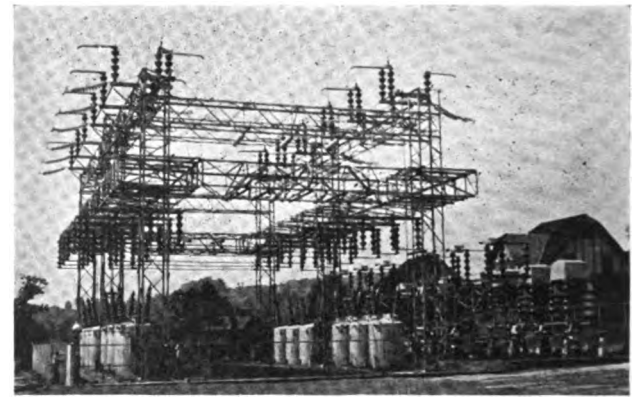
When a power company operates independently and its transmission system is not connected to the transmission systems of any adjacent companies, its problems of load regulation are comparatively simple. On such a system, assuming that all transmission lines are of sufficient capacity to carry any current that tends to flow over them, little regard need be paid to the flow of power. The flow may vary within reasonable limits without setting up any bad conditions. The division of load among power stations need not be watched as closely on an independent system as on a large interconnected system; there is no need to keep as close a check on the system frequency. It may vary a quarter or even half a cycle one way or the other without setting up any bad operating conditions. Therefore, the control of the load may be held at a point quite distant from the generators and the adjustment can be ordered on various stations over the system by the load dispatcher. The load dispatcher need not have any meters other than a frequency meter to note and regulate the fluctuations of the system load, he depending upon reports from his stations as to the load trend. The delay that results in regulating the load by remote supervision is not noticed on an independent system. Much of this regulation can be forecast and several plants can be changing the load at the same time, following a written schedule or a transmitted total load record as the system load varies.



THE 132KV/66KV INTERCONNECTION BETWEEN THE WEST PENN POWER COMPANY AND THE DUQUESNE LIGHT COMPANY

This interconnection is adjacent to the Colfax Station. The three single-phase, two to one ratio transformers are shown behind the three-phase tap-changing regulator.

As soon as a power company, maintaining such a system of load regulation, becomes interconnected with the system of another company, the troubles of each begin until they become educated to a more exact method of load adjustment and learn to maintain a more stable frequency. It is then found to be impossible for the various companies that were operating independently to continue their old methods and still to maintain the desired balance of flow of power across the interconnecting tie line. Close regulation of the load among the interconnected companies and among the power stations of each company proves to be the most difficult problem to solve.



THE 132 KV SUBSTATION AT THE LAKE LYNN STATION OF THE WEST PENN POWER COMPANY

The 66 kv system of the Monongahela West Penn Public Service Corporation is connected at this station to the 132 kv system of the West Penn Power Co. Leads from each bus go to two banks of three-winding transformers, the leads from the third winding connecting to the generator bus in the power station.

The next important factor to consider when several electric service companies are interconnected and operating in parallel, either continuously or for a few hours a day, is the frequency and its regulation. The loading of the power stations and of the tie lines between them depend upon this factor. It is impossible for one company to attempt to regulate the frequency and to keep a fixed frequency on their system when another company operating in parallel does not also regulate carefully, particularly if the company not regulating so well has the greater capacity, nor can two companies attempt to regulate the frequency independently of each other without getting into complications, unless unusual variations are allowed.

The only basis of load adjustment between two interconnected companies is the load on the interconnecting tie lines and if each company attempts to adjust the load on its stations independently of the other company, one company may be dropping load when the other company is picking up load. Suddenly a peak will be established on the tie line which may penalize one of the companies severely, especially if the billing of the power interchanged between them is based upon a peak demand. One company must maintain an established frequency, allowing the other company to vary

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its load to maintain a certain flow of power on the interconnecting line.

A company interconnected with more than one other company at different points is greatly limited in its ability to maintain load on the various interconnecting tie lines. This company can maintain without difficulty the load on the tie lines between its stations and the station or center maintaining frequency control, but companies interconnected to it and still farther away from the center of frequency control must regulate the amount of power flowing on the tie lines.

Any one company can regulate the flow of power from its stations by opening or closing the turbine governors which will tend to change the system frequency. The frequency adjusting station immediately observes the change in frequency and picks up or drops load to bring it back to normal. Such a change being made by the first station without the knowledge of the frequency regulating station will result in a variation of the frequency before it is caught. This variation will cause the load to vary on other turbines having sensitive governor adjustments all over the interconnected system, and numerous adjustments will have to be made before the proper divisions of load are re-established. A station raising its frequency will increase its output in all directions, and the power flow into other interconnected companies, away from the frequency control stations, will tend to increase. These companies possibly will adjust their governors to hold the tie line load normal which will tend to raise the frequency further, and then the load must be adjusted again when the control station drops load and brings the frequency back to normal.

An example of the above condition is as follows:—On the Duquesne—West Penn—Ohio Power System, adjustments in the load west of Windsor, the frequency controlling station, which caused the frequency to drop slightly, have caused Duquesne generating stations to pick up load automatically by the governors in an attempt to maintain 60 cycles, and to feed power into West Penn until the Duquesne governors were readjusted to place the proper load on the tie lines. A short time later Windsor station would raise the frequency to normal and the load picked up would flow through West Penn into the Duquesne System until the Duquesne governors were adjusted again to bring the load on the tie line back to normal. This operation has created several peaks between the different companies which were difficult to adjust when the billing was discussed. If the frequency had been maintained at 60 cycles and the outlying company had maintained the adjustment on the interconnecting tie instead of the company in the center, the load equilibrium of the other companies would not have been disturbed.

Successful operation should include the following practices: All parties should agree to hold their base frequency, allowing very little variation. One generating station of suitable capacity should be assigned the task of holding the frequency steady and controlling the regulation, and this center will pick up or drop load within the economic or capacity limits of the station to maintain and hold the frequency constant. If the frequency is high and the stations controlled by the operating center cannot drop economically any more load to lower the frequency, one of the other companies or generating stations must be ordered to drop load to bring the frequency back to normal. If the frequency is low and the controlling power stations are over-loaded, the adjacent companies or generating stations must pick up load.

THE 132/110 KV INTERCONNECTION BETWEEN THE WEST PENN POWER COMPANY AND THE PENNSYLVANIA ELECTRIC COMPANY
Located at the Piney Station of the Pennsylvania Electric Company. The 110 kv bus of the Pennsylvania Electric Company is on the left and 132 kv bus of the West Penn Power Company is on the right.

The frequency regulation can be changed from one generating station to another as the system load changes, either upon orders from the operating center or by following a predetermined schedule. Various stations may vary the load in proportion to a certain percent of the system load, making their adjustments without orders as the system load changes, but the frequency control should be confined to one station.

Companies or generating stations not controlling the frequency may vary their load as the load on their system varies, being governed by the flow of power in the interconnecting tie lines. They must hold the load on these lines close to the predetermined values except when the load on the constant frequency station goes above or below certain predetermined economical values. Upon any serious trouble causing the frequency to fall, all stations must automatically pick up load within their capacity limit to restore the frequency

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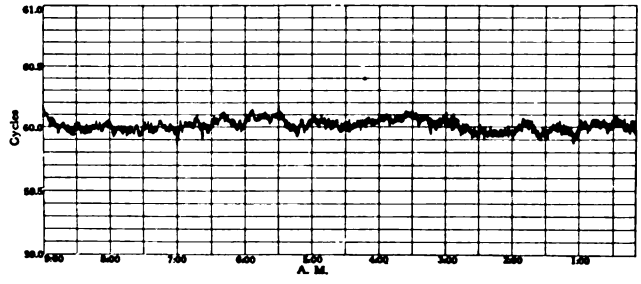
to normal. During such emergencies little regard is paid to station efficiencies or the loading of tie lines so long as they do not exceed their safe values, this being determined usually by the relay settings on these lines.

When several companies are connected together in a long string or radiating out from a center, a station of sufficient capacity near the center of the interconnections generally is the most suitable place to maintain control of the frequency. This station can vary its load to maintain the constant frequency with a minimum of load variation on the interconnecting transmission lines. The outlying companies then simply need to vary the loads on their stations as the loads on the interconnecting tie lines vary and the transfer of load from one system to another can easily be maintained at its desired values.

The governors on the units at the frequency regulating stations should be set to be slightly more sensitive than the governors at base load stations to allow the frequency controlling stations to take the load




A TYPICAL CHART OF THE FREQUENCY OF A LARGE INTERCONNECTED SYSTEM

At 6:40 A.M. a steam driven generator tripped off the line while carrying 40 000 kw. At 6:56 A.M. two large systems were paralled over a 132 kv tie line interchanging 30 000 kw.

swings. The fact that the governors on the units on the Duquesne System are slightly more sensitive than the governors on the base load plants on the West Penn System is believed to cause load variation on the West Penn—Duquesne tie line at times of slight frequency variations. When two companies operate together only part of the time the governor settings must be planned to cover two different conditions—independent operation and parallel operation and the subject is one which might be studied more fully to advantage.

The problem of frequency control has been simplified greatly by the recent development of a frequency regulating motor which is installed in the turbine governor to maintain automatic frequency control. The installation of automatic frequency control makes it possible to obtain a much smoother frequency curve than when manual adjustment is depended upon. The automatic control is sufficiently exacting when properly adjusted to permit the frequency regulation to be maintained at more than one station, if the loads on the tie lines between the stations do not limit load variations.

The frequency of the Pennsylvania Power & Light Company and the interconnected systems is being controlled at the Wallenpaupeck station by a governor regulating motor installed on one of the hydro turbines. The frequency is being maintained continuously within a range of ± 0.1 cycle from 60 cycles and averages within ± 0.05 cycle from 60 cycles. This is closer regulation than is being obtained at present by manual control on the West Penn System.

The development of very sensitive frequency meters registering fluctuations of 1/100 of a cycle and frequency clocks which constantly register the total variation of the frequency, if any, make it possible to maintain very close regulation. When several power companies operate in parallel and over 1 000 000 kw in capacity are tied together, the troubles of one company are smoothed out by the generating capacities of the others; and it is surprising how flat a curve can be maintained on a sensitive graphic frequency meter.

Good operation requires not only that the frequency be maintained at exactly 60 cycles on a 60 cycle system, but that any frequency variations be compensated by a frequency clock, which should be checked continuously and not allowed to vary over five seconds. With such regulation, frequency clocks can be installed at all stations with the knowledge that all the stations will have an accurate record of the time of their operations, when recording various reports. A variation of as little as one-twentieth of a cycle from the frequency to be held, will cause a redistribution of the load on any tie lines between large generating capacities and necessitates adjustment of the turbine governors, which will have to be changed again when the frequency returns to normal.

During periods of system load changes, the load on the Duquesne-West Penn tie line has swung up to 15 000 kw with frequency changes of only about one-twentieth of a cycle.

On a large interconnected system, it is an extreme case of trouble that will cause the frequency to drop even momentarily as much as one-quarter of a cycle. Generating units of 40 000 kv-a capacity, on such a system, have tripped off the line when operating at full load without causing the frequency to drop this amount. Such close regulation has been maintained that the interconnected system has operated for days without a total variation of over five seconds from 60 cycles. Operating at 59¾ cycles for one hour would cause the frequency clock to lose fifteen seconds.

The problem of maintaining a flat compensated frequency has worked out so satisfactorily that many companies have actively undertaken the selling of these frequency-regulated clocks to their consumers and time service is another of the new responsibilities assumed by these companies. It is not unusual to listen in on the radio and receive the correct electrical time being broadcast as maintained by some electric service company. The furnishing of time service to consumers and the selling of telechron clocks is not directly a problem of interconnection operation, but the practices

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which have resulted and which are applied to both subjects, make the subjects of "electric time" indirectly a part of the problem being discussed.

The accuracy of "electric time" on the West Penn System is maintained by receiving the time signals twice daily by radio from the Government Station at Arlington and transmitting these time signals over the companies' telephone lines to all master stations, who check together their clocks and assure themselves of the accuracy of the electrical time. If there is any variation between the electrical time and the time as received from Arlington, no attempt is made to correct the time immediately by radically adjusting the frequency. The frequency is just altered slightly and the adjustment is spread over several hours unknown to any consumer or interconnected company not watching frequency regulation closely. It has been found necessary to use the time signals as received from Arlington as the basis for frequency regulation, as no other time service available has been found sufficiently constant to meet the standards now maintained.

The furnishing of "electrical time" to the power consumers has brought two more problems of operation before the utility companies to maintain satisfactory service; that of the stopping of all electric clocks when a circuit is interrupted, for occasional interruptions are inevitable; and second that of paralleling two systems that have been maintaining separate time. Neither problem has developed any serious difficulties as yet.

Maintaining electrical time simply requires that the frequency and duration of interruptions to consumers must be further reduced to a minimum whether the service is domestic or power load, but this naturally is the intent of all electric service companies. Consumers are made aware that interruptions have occurred by the registering of a target in the electric clock. Following any interruption, the correct time can be obtained and the clock reset by calling any of the power companies' offices or substations or by obtaining the time over the radio.

When two parts of a system which have been maintaining independent frequency control are to be paralleled, it is necessary that the electric clocks on the two systems register the same time at the time of paralleling, though the time of both systems may vary from the correct time by a few seconds. During normal operation this problem is not difficult for neither system should vary from the correct time more than a few seconds and the smaller system of the two will adjust its frequency just before paralleling to speed up or slow down its clocks until both times are identical.

When any part of a system is separated, following a severe case of trouble, an unequal division of generating capacity may cause one part to operate at a low frequency until the two parts are reparalleled or additional capacity is placed on the line. The necessity of maintaining system stability at such times will necessitate that a little thought be paid to any variation in the electrical time that will result. This variation in time can be corrected later by separating the systems during a period of light load in the same manner that they separated during the trouble, adjusting the frequency on one part until the clocks again are identical and then reparalleling.

The failure of important transmission lines on the West Penn System during a recent severe storm caused the system to separate three ways and operate separated about thirty-six hours, or until the lines could be repaired. During this time, each system maintained its frequency independent of the other, and when the checks were made before the two largest divisions were paralleled, the time at the control points varied only fifteen seconds which was adjusted in about ten minutes. The time on the smaller division varied nearly two minutes, but this was corrected in about half an hour and all clocks were together when the system was again tied together.

Each company operating in parallel with other companies generally desires to maintain the regulation of its voltage independent of the other interconnecting companies according to its system load and flow of power at the time. Independent voltage regulation is impossible when the interconnecting tie lines connect directly to the station buses of each company, for such regulation will cause a varying amount of reactive power to be interchanged between the two companies, the company maintaining the higher voltage at the time absorbing the reactive current of the other.

The installation of regulator transformers in the interconnecting transmission lines satisfactorily solves the problem of independent voltage regulation and of the interchange of reactive current. The tap settings on these transformers are varied under load to maintain a certain power-factor on the line, the minimum power-factor to be maintained usually being pre-determined by the interchange agreement between the companies. A total regulation of twenty percent can be obtained by these regulators and transformers which insures that the reactive current will be properly divided between the companies irrespective of their load or the load on the interconnecting lines between them. Installing an adjustable regulator at one end of interconnecting tie lines between two systems generally is the recommended practice.

Systems operating at different frequencies can operate in parallel through frequency changers, the amount of power exchanged between the systems being limited by the capacity of the frequency changers in operation. When variable ratio frequency changers are used, considerable flexibility is obtained. In fact, with this type of equipment, two systems may vary their frequency independently of each other and still remain in parallel, the variation being absorbed in the slip of the frequency changers.

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Interchange agreements usually exist between the operating companies which determine the plan of operation and the loading of the interconnecting tie lines. These interchange agreements are based upon many different plans, but whether it is the intent for one company to purchase a block of power from another or for the two companies simply to operate in parallel without any exchange of load except in an emergency, namely to utilize each other's reserve, the basic plan of operation will be the same. Lack of experience at the time of drawing up some of the interchange contracts in existence today has resulted in numerous operating problems which possibly could be greatly simplified if the contracts were changed.

The interconnections among power companies that have been established with satisfactory operating results have been only tie-ins between groups of companies forming one long string, with other companies tied to the string, as branches at different points. The writer has no knowledge of any interconnections between several companies with a closed loop where satisfactory operation can be maintained. Several such loops are in existence, and the West Penn System is a part of one such loop, but normal operation is with the loop open at one place or another. Designs for equipment to regulate accurately the flow of power under all conditions over such loops have been worked out and the capacity of the equipment necessary has been determined, which likely will be installed in the near future. The flow of power in a closed loop will be toward a center, which can change as the system load varies. This load will tend to flow from the generating stations the shortest distance around the loop to the center.

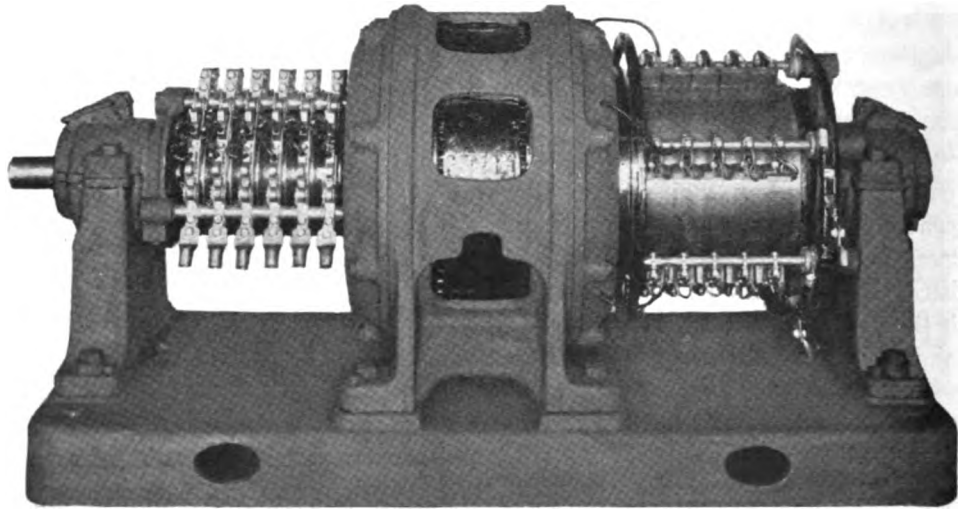
The problems of connecting together systems of different voltage or different frequencies are not dwelt upon at any length by the writer as these two problems are questions of engineering design rather than operation, dependent upon the individual characteristics of the various interconnections. The problem of the restriction of short-circuiting current flow between systems upon transmission failures has not been discussed as this also presents a problem that is solved before interconnections are placed into service. As yet, the short-circuit currents that exist have not created any serious trouble, the modern equipment having been designed to prevent this. The length of the average high voltage interconnection assists materially in restricting any possible high short-circuit current flow.

# Dual-Frequency Calender Drive

S. G. NOTTAGE
Industrial Motor Engineering Dept.,
Westinghouse Electric & Mfg. Co.

THE calendering of paper requires a low speed for threading the paper between the rolls, in addition to the high speed for the actual calendering after the paper has been threaded. Until the development of the dual frequency drive, this low speed had been obtained either by an additional small motor with suitable gearing and over-running clutches, or else by using one motor for both high and low speeds with additional back gearing and clutches on the low speed.

The dual frequency drive uses only one induction motor permanently geared to the calender and obtains the low speed by supplying the motor with reduced voltage and frequency, which is generally about one-tenth of the supply frequency. This system permits the use of modern totally enclosed speed re-



A PEDESTAL-TYPE FREQUENCY CONVERTER

Which runs at 690 r.p.m. on 25 cycles. The armature is similar to that of a synchronous converter, but the commutator has three brush arms for every two on a converter.

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duction gearing, making a much quieter and cleaner drive than the old type open gears.

The performance of the induction motor on this low frequency is generally found to be satisfactory. The influence of the primary and secondary resistances is very marked on the low frequency operation, because the voltage induced by the field at low frequency is low, and the resistance drops become comparable in magnitude to this induced voltage. The primary resistance decreases the maximum torque considerably. On a 60 cycle equipment this loss of torque can be counteracted by applying higher voltage, but on some 25 cycle equipments it may be necesssary to modify the design to provide a lower resistance stator winding. The rotor resistance also on 25 cycles may reduce the maximum available starting torque, but this has never been found to be of much importance. In some cases which have called for excessive starting torques, the only way to obtain this torque is to apply a higher voltage to the motor. Under these conditions, due to saturation in the magnetic circuit, the motor may draw more current at no load than at starting. It is necessary to figure on a transformer in the low-frequency circuit to supply a running voltage less than the starting voltage.

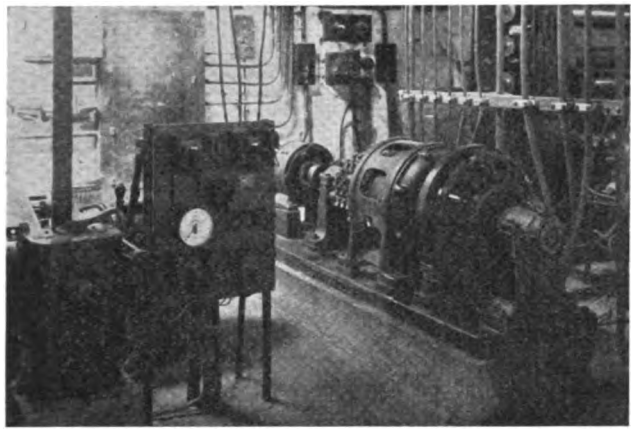

FIG. 1—THE FIRST FREQUENCY CONVERTER INSTALLED
Which is separately driven by a direct-current motor.

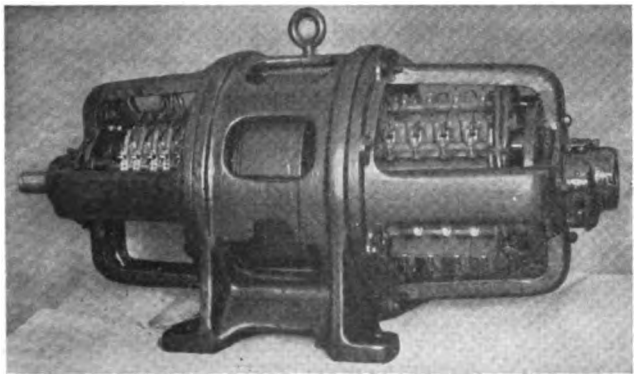

FIG. 2—A FOUR POLE BRACKET-TYPE FREQUENCY CONVERTER
Which runs at 1680 r.p.m. on 60 cycles.

The generation of this low-frequency current is possible either in a commutator machine or in an induction machine. Since the low frequencies required are close to direct current, it is apparent that any machine in which a voltage is induced in the conductors by a rotating field, such as a synchronous generator, will be inefficient and becomes impossible on direct current, which may be regarded as zero frequency. There are only two practical types of commutator machines which can be used, the frequency converter and the self-excited polyphase commutator machine. The frequency converter is a very stable and easily controlled machine, having operation and characteristics similar to a rotary converter. The self-excited polyphase commutator machine is somewhat similar to a direct-current generator with, however, the serious objection of having to control the generated frequency.

The characteristics of the frequency converter and the synchronous machine for generating frequencies of the order of 1.5 to 6 cycles are somewhat different. The frequency converter runs at practically synchronous speed of the supply, and is therefore a high-speed machine. The synchronous generator must run at synchronous speed of the low frequency. Since the outputs required are of the order of 30 to 75 kv-a, it is not economical to build a synchronous machine of large diameter. This will mean that the peripheral speed will be low, giving very inefficient utilization of the electromagnetic material and a high internal resistance drop.

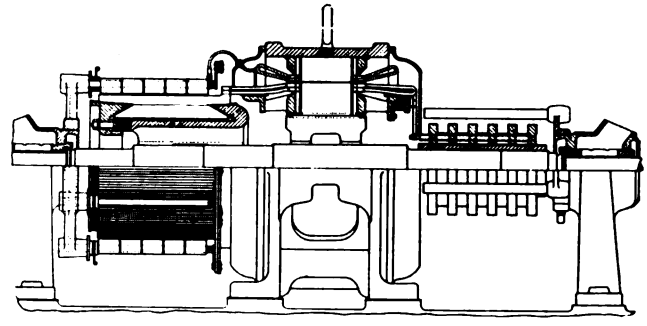

FIG. 3—A LONGITUDINAL SECTION OF THE PEDESTAL-TYPE FREQUENCY CONVERTER

The efficiency of the frequency converter including transformer is about 85 percent, whereas the synchronous machine including driving motor will not be above 70 percent. This is on the basis of a four-cycle machine. For lower frequencies the efficiency of the synchronous machine gets rapidly worse; whereas that of the frequency converter is not affected. Another important characteristic is the voltage regulation, which is about eight percent drop from no load to full load on a frequency converter; but on the synchronous generator the drop will be large enough to cause unsatisfactory operation, due to the induction motors not developing enough starting torque on the reduced voltage when the generator is overloaded.

The voltage required to operate an induction motor on these low frequencies is somewhat larger than that obtained by figuring in proportion to the frequency reduction, due to the fact that at low fre-

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quency the ohmic drop becomes comparable in magnitude to the induced voltage. For example, a 440 volt, 60 cycle motor operated on 6 cycles will require about 60 volts instead of the 44 volts which would be obtained by figuring the voltage as proportional to the frequency.

The general construction of the frequency converter is shown in the illustrations. It is a well understood feature of a converter that at standstill the frequency on the commutator is the same as on the slip rings, and that this frequency diminishes to zero as the machine comes up to synchronism. To obtain a definite frequency the armature must be driven at a constant speed slightly different from synchronism. This can be either above or below synchronism, but is usually chosen below synchronism and is given as follows:—

$$R.P.M. = \frac{(Slip\ Ring\ Frequency \pm Comm.\ Freq.) \times 120}{Number\ of\ Poles}$$

Thus, a four-pole machine with 60 cycles on the slip

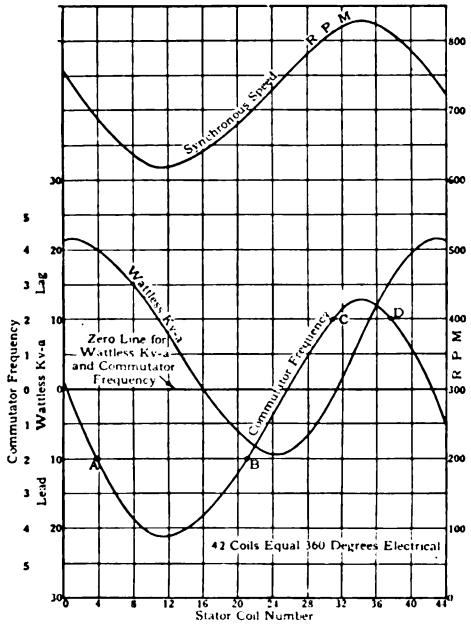


FIG. 4—THE VARIATION IN SPEED, COMMUTATOR FREQUENCY, AND WATTLESS KV-A OF A FREQUENCY CONVERTER WITH TAPPING POSITION

rings and four cycles required from the commutator will have a speed of,—

$$60 \pm 4 \times \frac{120}{4} = 1920\ or\ 1680\ r.p.m.$$

Due to having only two brushes per pair of poles, the synchronous converter will only give single-phase at the commutator. The use of three equally-spaced brushes on a frequency converter enables us to obtain three-phase currents.

The frequency converter requires only enough torque to drive it against friction and windage, and does not theoretically require any more torque when loaded; but in practice it is found that the torque does vary somewhat with the load. The machine shown in Fig. 1 is driven by a small direct-current motor which, while operating satisfactorily, leaves the control of the low frequency up to the operator. This has proven disadvantageous and to make a more fool proof machine the self-driven type was developed.

The stator construction of the machine in Fig. 1 is simply a ring of iron with notches cut in to provide a zone of reduced flux, which helps the commutation. The self-driven machine, Fig 3, has a winding in the stator similar to that of an induction motor and, if the commutator is disregarded, this machine is exactly the same as an induction motor with power fed to the rotor slip rings, and the rotor acting as the primary. If resistance is connected across the stator, the rotor will come up to speed and can be regulated to give the required speed below synchronism, the reduction in speed being due solely to the friction and windage torque. If the frequency converter commutator is loaded, and some torque, for instance two percent of rated output, is developed, this is approximately equal to the friction and windage and would cause the slip to double, thereby doubling the commutator frequency and giving unsatisfactory operation. To prevent this a machine has been developed which would drive itself at the correct speed, regardless of the load passing through it. To accomplish this, the stator winding is designed so that at the required slip its induced voltage is about the same as the commutator voltage. Then, instead of absorbing this slip voltage by resistance, the stator is connected to the commutator in the correct phase and the commutator voltage regulates the speed the same amount regardless of load, since the commutator voltage remains constant.

By designing the stator winding so that the commutator voltage is somewhat in excess of that required to give the correct slip, and then, by adjusting the phase, the power-factor of the frequency converter can be improved so that it will draw a leading current from the line on no load. This adjustment of phase is obtained by connecting the stator winding in a continuous ring and then taking taps off at equidistant points, to the commutator brush arms. These tapping points can be moved around, thereby giving a continuous adjustment of phase. When the point giving the correct speed is found, the connection is made permanent. The curve in Fig. 4 shows the variation in speed, commutator frequency and wattless kv-a, as the tapping points are moved around. The starting point can be anywhere, but the curve shows a movement of the tapping point over two poles pitches or 360 electrical degrees, after which the curve will repeat itself.

It will be noticed that there are four positions, *A*, *B*, *C* and *D*, which give the correct commutator frequency. *A* and *B* are both obtained with the frequency converter running below synchronous speed, but position *A* draws a large lagging kv-a from the line, while *B* draws leading kv-a from line. Similarly, points *C* and *D* are obtained, giving the correct frequency with the frequency converter running above

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synchronism. Position *C* draws practically no wattless kv-a from line and position *D* draws a large lagging kv-a from line. The point *B*, giving the best power-factor below synchronism, is the one usually chosen, principally in order to keep down the peripheral speed of the commutator.

These machines commutate very well; the first machine installed in the early part of 1923 is still using the original set of brushes.

The frequency converter for generating low frequency currents to supply the primary of an induction motor has also been experimentally applied to give slow-down speed for elevators and skip hoists and works very satisfactorily.

# Piezo-Electric Frequency Control

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When used under the proper conditions, quartz crystal oscillators are now recognized to be one of the most reliable means for controlling radio broadcast station frequencies, where a precision better than 0.1 percent is desired. Frequency precision as good as 0.001 percent has been attained in laboratory oscillators. Under the more severe conditions of constant use and with less care than is usual in a laboratory, a radio station affords a good test of the reliability of a quartz crystal oscillator. The following article covers the results of measurements made of KDKA's 950 kc. frequency for a period of six months.

THE use of a crystal oscillator for station use is termed "automatic piezo control"[1] as the radio frequency does not have to be watched as closely as when using a tuned condenser and coil. In addition to the automatic piezo control, KDKA is "crystal checked" by three crystal oscillator standards, calibrated by the Bureau of Standards.

Due to the presence of blast furnace gases in the Pittsburgh district, it was found necessary to use a special type of sealed mounting[2] for all crystals whose calibrated value was to be maintained.[3] It is very important to keep the temperatures practically constant at a point where the crystal has no abrupt frequency jumps with small temperature changes. The knowledge of the relative importance of various factors has been used in designing standard crystal oscillators which are used for checking purposes and the crystal control equipment used at radio station KDKA.

Relative measurements show the precision of frequency maintenance of KDKA to be ± 0.0042 percent over a period of six months. Expressed as a frequency, a 0.0042 percent deviation from the assigned value of 950 000 cycles per second is 40 cycles per second. These frequency determinations were made by measuring the audio frequency beats between the calibrated standards and the frequency of the station in a manner already described.[3]

The order of magnitude of deviation of only 0.0042 percent is perhaps more easily realized by an illustration. Suppose the range of frequencies from zero to 1 500 000 cycles per second be represented by a five foot bookshelf filled with magazines. If each page represents 50 cycles per second, and the pages are two thousandths of an inch thick, the bookshelf will contain 30 000 pages. Assuming an average of 100 pages per month, this would represent copies of the magazine for twenty-five years. The present broadcast band of 550 to 1500 kilocycles per second would include the pages numbered from 11 000 to 30 000. Dividing up the band into ten kilocycles divisions means assigning 200 pages to a station. It is understood that the station maintains a carrier frequency at the assigned value, with audio frequency variations from it, depending on the program being sent out. Using the analogy, the station frequency is a certain page, while its audio frequency modulations may change the frequency as much as 100 pages either way.

The Federal Radio Commission has specified that the absolute value of the assigned radio frequency must be within 500 cycles per second of the correct absolute value. This corresponds to ± 10 pages, or the station must be kept at its proper position in the bookshelf within 10 pages.

KDKA has been assigned 950 kilocycles per second, corresponding to page 19 000 on the hypothetical magazine collection; and if the Commission's requirements are to be followed, KDKA should be kept between pages 18 990 and 19 010. The actual precision of location was determined by the calibration data of the Bureau of Standards given for the three standard oscillators. The day to day, or relative precision, can be measured accurately by audio beats between station and standard, as already mentioned. For tests over six months, the 0.0042 percent variations, or 40 cycles per second, means that from day to day, KDKA varies a maximum of four-fifths of a page from its mean position.

[1] A quartz crystal is piezo-electric, hence piezo control = crystal control.

[2] *Proc. I.R.E.* Nov. 1927, page 902.

[3] Other factors affecting crystal frequencies have been treated in the JOURNAL for September 1927, p. 430.

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# System Stability with Quick-Response Excitation and Voltage Regulators

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Westinghouse Electric & Mfg. Co.

During the last several years, many analytical and experimental investigations have been made and reported covering the operating phenomena of heavily loaded long transmission lines and of shorter high impedance tie lines. Recent literature on stability has introduced or suggested some new terms that as yet do not appear to have crystallized into universally accepted usage. Therefore, the following introductory paragraphs cover certain of these terms as understood in the discussion following.

WHEN an artificial line is used to transmit power from a synchronous generator at the sending end to a synchronous motor at the receiving end, or when an actual system is used without voltage regulators, the voltage may be corrected by hand from time to time as the transmitted power is gradually increased by loading the receiving end. While the excitation is slowly increased by hand as load is raised, no attempt is made to over-regulate but merely to keep the line voltage constant, or the excitation fixed, at any given steady load value. With a uniform or steady load thus gradually increased under fixed excitation or non-regulated conditions, the rotor of the receiving

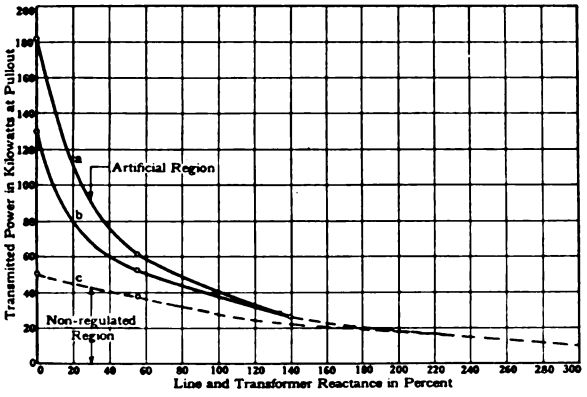
Transmitted Power in Kilowatts at Pullout
Artificial Region
Non-regulated Region
Line and Transformer Reactance in Percent

FIG. 1—STEADY-LOAD POWER LIMITS AS AFFECTED BY LINE REACTANCE

(a) Adjustment most favorable to steady-load performance.
(b) Adjustment most favorable to transient performance.
(c) Non-regulated steady-load power limit.

machine gradually assumes a greater relative angle of lag behind the generator rotor until it can no longer remain in synchronism, and pullout occurs.

Operation up to the point of pullout under the above mentioned conditions may be referred to as within the region, or below the limits of *non-regulated steady-load stability* (Fig. 1); and the maximum power thus transmitted at the point of pullout, as the *non-regulated steady-load power limit* of the system. For example, from Fig. 1, with a 55 percent reactance line, 38 kw is the non-regulated steady-load power limit for the system of machines, lines, etc., covered by the data shown.

With load set at some initial value a little below the non-regulated steady-load limit, a sudden disturbance would cause the system to swing, and the rotors of both machines to oscillate about their mean or steady-load position. If the disturbance is severe enough, such oscillations will cause the rotors to reach a total angle great enough to cause pullout. If the severity of the disturbance can be evaluated or if all surrounding conditions are completely described, then the maximum initial load which can be transmitted without causing pullout when the transient disturbance is applied, may be referred to as the *non-regulated transient power limit* for these conditions.

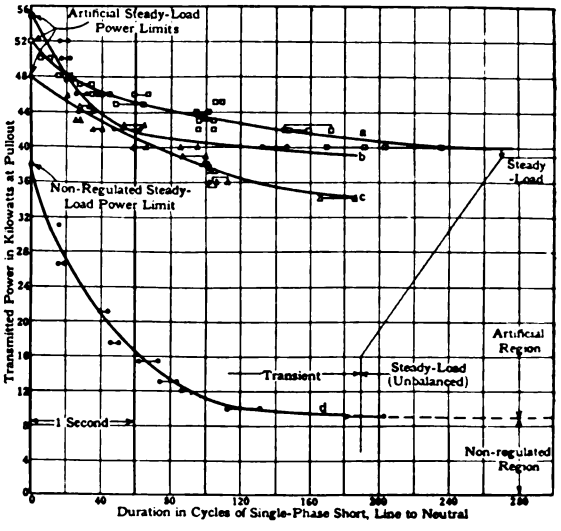


FIG. 2—TRANSIENT POWER LIMITS, 55 PERCENT REACTANCE LINE

(a) 525 volts excitation, voltage regulator adjusted for best transient performance.
(b) 525 volts excitation, voltage regulator adjusted for better steady-load performance.
(c) 130 volts excitation, voltage regulator adjusted for best transient performance.
(d) Non-regulated transient power limit.

The transient power limits for a given set of machines are shown in Fig. 2. On curve (d) 38 kw is the non-regulated steady-load power limit (zero disturbance); and the curve shows how the non-regulated transient power limit varies with increasing duration of the type of disturbance here applied. Thus, the non-regulated *steady-load* power limit is a special case or one point on the more general and variable non-regulated *transient* power characteristic curve. It should be noted further how the curve approaches a value of power that can be transmitted continuously without pullout. This again becomes

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a steady-load condition, being a case of an unbalanced load due to the single-phase fault hanging on.

If the machine excitations are not fixed, but are under the control of voltage regulators, conditions are quite different. The load may be increased beyond the non-regulated steady-load power limit before pullout occurs. When the rotors start to pull apart, the effect of a voltage regulator is to so raise or control the excitation as to pull them in or keep them in step. That is, the rotors are continuously swinging in a state of unstable equilibrium, similar to a rod balanced upright by spring supports or props on opposite sides. However, a higher power limit is again reached by further increasing the load, where the system is overtaxed and pullout occurs. Operation up to this point of steady pullout with the regulator and above the non-regulated steady-load limit, may be referred to as within the region or below the limits of *artificial steady-load stability;* and the maximum power thus transmitted, as the *artificial steady-load power limit* of the system.

Similar to the non-regulated transient power limit, there is also a higher limit called the *artificial transient power limit* for given disturbance conditions when a voltage regulator is in control. Thus, curve (a), Fig. 2, while the artificial steady-load power limit (zero disturbance) may be 52 kw with a given system, (including regulator), when a disturbance of 40-cycle duration occurs the artificial transient power limit is 46 kw for the same system.

### QUICK-RESPONSE EXCITATION

Since quick-response excitation was first pointed out as useful in connection with system stability, i.e., as offering improvement in the operating conditions of certain systems, more or less confusion has come to exist as to just what constitutes quick-response excitation. It is not here thought of as some newly discovered and abstruse improvement on the work of Maxwell, Helmholtz, Tyndall, etc., on fundamental and general electrical circuits. In general, d-c circuits of low time-contant and, therefore, fast buildup rate, have long been known and, of course, have been quite extensively applied for a large variety of purposes. Even in a-c systems, exciters having a certain rapidity of buildup have been applied occasionally to minimize voltage disturbances, or restoring voltage to normal more quickly after the application of a sudden load, or for special applications aside from the usual power transmission systems. But prior to the introduction of quick-response excitation systems, there had been no thought of operating a system at a greater phase-angle displacement, between generator and motor, than that corresponding to the maximum power obtainable with fixed excitation.

However, such prior applications do not at all constitute quick-response excitation in the sense in which this term has more recently been used. Obviously, one machine, an exciter of rapid buildup rate, cannot be called a quick-response excitation system. A system implies more than one machine or element. A quick-response excitation system would include at least a source of excitation such as a battery, excitation bus, or auxiliary constant-voltage exciter; a main exciter, which must have a rapid operating buildup rate; an a-c generator to be excited; and a voltage regulator of the proper characteristics, the purpose of such a combination being to improve the overall transmission system stability, chiefly transient stability. It might also include an auxiliary a-c generator supplying the motor-driven main exciter, and a regulator therefor. The system is termed quick-response by virtue of the fully-utilized unusually fast, actual operating buildup rate of the exciter, however secured—perhaps by special design—and not because of a potentially fast buildup rate which is never actually utilized by the operation of the combined exciter and regulator circuits.

It is this application and utilization of an exciter of unusually rapid buildup rate in such a combination that is known as a quick-response excitation system. In this sense quick-response was new. The following facts are now quite generally recognized with regard to the application of quick-response excitation:—

1—Some systems would not be benefited to any appreciable extent, economically;

2—Others are borderline cases and a matter of judgment;

3—In still other cases, quick-response excitation is of material advantage in improving system stability.

Therefore, the field covered by quick-response excitation is that of the transmission line and generating equipment as an operating combination or unit, commercial apparatus and not academic theoretical circuits. The usual sizes of exciters involved are not small, such as five kw machines, but more nearly of ten times that capacity or larger. In addition, when referring, for comparison, to the speed of response of standard exciters, self-excitation is understood; and the field coils are almost always connected in a single circuit unless split into parallel field circuits for the purpose of increasing from ultra-slow response to standard slow-response applications.

When considering the buildup possibilities of standard exciters as they have been generally used before the development of quick-response excitation, it should be clear that unusually fast response was not the object of the design *per se*. As stated above, one field circuit was the usual connection and self-excitation was general. Furthermore, for such machines in capacities of 50 kw or larger, it has been shown that the maximum buildup rate is of the order of 80 percent of rated voltage per second, or 200 volts per second for 250-volt exciters. It is only by considering high speed turbo exciters and capacities rather below those involved in quick-response and transmission line stability that operating buildup rates somewhat higher than 200 volts per second are en-

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countered. Thus, a five kw exciter would have a maximum buildup rate of about 110 percent of rated voltage, or 275 volts per second. At the other extreme would be found larger, slow speed exciters building up (at rated voltage) at a speed of ten percent of rated voltage per second, or 25 volts per second even for 250-volt machines. Therefore, with 200 volts per second as an upper limit, standard or slow-response rates of buildup vary down to 25 volts per second or less. However, these buildup speeds of 150 or 200 volts per second are not made available for quick-response excitation unless the voltage regulator has the proper characteristics.

As to quick-response buildup rates, the range of quick-response quantitative values can be stated less definitely than those of self-excited or slow response. This is because, "Any excitation system—which, of course, includes the regulator as well as the exciter—which is sufficiently quick as to make an important change in the excitation voltage before the synchronous machine has had time to swing to a dangerous angle, beyond which recovery would be doubtful, is quick-response. Or, considered from the standpoint of the fluxes in the synchronous machine, any excitation system that is quick enough to prevent a significant reduction in flux interlinkages due to demagnetizing armature current, as from a short-circuit or other system disturbance, is quick response." However, it is well-known that to accomplish this purpose voltage regulators, supplied as a part of quick-response excitation systems, are used to control exciters that are many times quicker in response than those previously used with normally-excited generators. It may thus be conservatively stated that the operating buildup rates involved in quick-response excitation are 200 volts per second, or higher.

In view of the above, whatever may be the upper limit of values of quick-response excitation, there should be no doubt as to where sluggish response

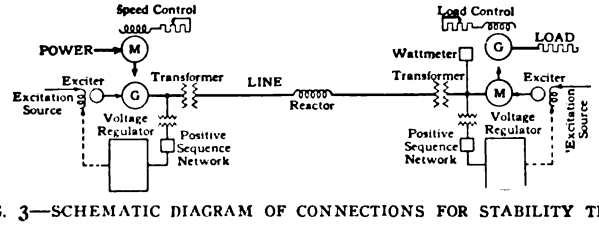


FIG. 3—SCHEMATIC DIAGRAM OF CONNECTIONS FOR STABILITY TEST
Using duplicate motor-generator sets composed of 220 hp alternating-current machines and 150 kw direct-current machines.

ends and quick-response begins, when considered with reference to quick-response excitation systems. This dividing line can be stated quite clearly as 200 volts per second. It should also be clear that self-excitation must be abandoned and special or unusual means resorted to, such as separately-excited exciters, or special design, or both, in order to obtain quick-response rates of voltage buildup, especially if 200 volts per second is desired as an initial rate from the lower excitation voltages. One convenient method, is that of parallel field circuits. If two field coils are connected in parallel instead of series, no external resistance being used in either case, $L/R$ remains unchanged. Since $L$ and $R$ are each halved by this reconnection, their ratio is of course unchanged. However, the operating time

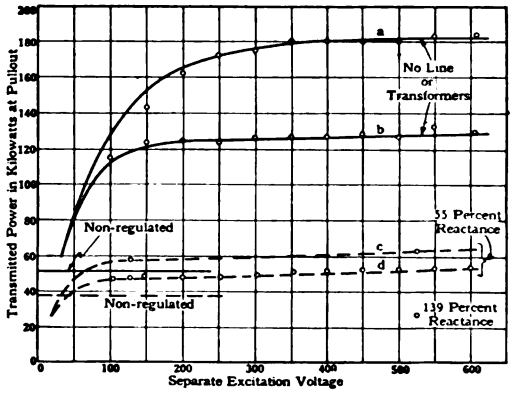


FIG. 4—ARTIFICAL STEADY-LOAD POWER LIMITS AS AFFECTED BY SPEED OF RESPONSE
(a) and (c) Adjustments made most favorable to steady-load performance.
(b) and (d) Adjustments made most favorable to transient performance.

constant is changed because, after being reconnected in two circuits, more external resistance must be used to cover the same operating voltage range, or to limit the current carried by the regular contacts.

## TESTS WITH VOLTAGE REGULATOR

With the foregoing principles in mind, a laboratory test setup has been made, as shown schematically in Fig. 3. In running curves (a) and (b), shown in Fig. 4, the transformers and reactors were not in use, the generator and motor being connected solidly together; also only one regulator and exciter was used for both machines. The procedure was to apply a certain value of excitation bus voltage to the exciter, then, while holding the frequency constant, to increase load on the motor or receiving end until pullout took place.

Curve (a) Fig. 4 was made with one voltage regulator adjusted for best steady-load performance as shown. However, as described later, when testing transient performance other adjustments were required for best transient results. When so adjusted, the corresponding steady-load results are given by curve (b). The general effect of increasing the speed of response is clear. (In practice the exciter fields are designed or connected to give an equivalent speed of response from a lower excitation voltage.) It should be noted that, as higher and higher excitation voltages were used, fixed resistance was added in the exciter field circuit so that the range of exciter armature voltage from open contacts to closed contacts was always the same. Also, in order not to overload the direct-current machines, the alternating-current machines were operated at half rated voltage.

Then the line and transformers were inserted giv-

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ing 55 percent total reactance, based on the rating of the machines, and both regulators and exciters used, as shown by Fig. 3, and similar data taken as shown by curves (c) and (d) of Fig. 4. It is evident that a line considerably reduces the artificial steady-load power limit.

In order to carry the tests far beyond the limits which would usually be encountered in practice, and with the purpose of obtaining all possible data on quick-response excitation—even beyond the range of actual design, because a long transmission line would invariably be broken up into a number of shorter sections by means of intermediate condenser substations—the connections were then changed to obtain 139 percent reactance based on the rating of the machines; and the artificial steady-load power limits were determined for 525-volt excitation.

Fig. 1 shows this limit, also the corresponding 525-volt values from Fig. 4, plotted as curves (a) and (b). Curve (c) shows the non-regulated steady-load power limit, i.e., with no regulators but with hand correction of alternating-current voltage as load was increased slowly to pullout. Thus, curve (b) is the important one, showing the artificial steady-load power limit when the regulator is adjusted properly to handle transient disturbances.

In an actual system, on account of the different characteristics of large machines as distinguished from the small test machines used, Fig. 1, curves (a), (b), and (c) will tend to come together. On the other hand the multiplicity of generators on the bus will offset this tendency to some extent. However, the steady-load power limits, Fig. 1, are relatively unimportant, as distinguished from the transient power limits, because at present very few, if any, important systems are operating anywhere near the non-regulated steady-load power limits, as these limits cannot be approached in practice because of the margin which must be allowed to take care of transient disturbances, so that the transient power limits really become the practical limits of the system. Moreover, a transmission line must always be operated so that it can lose one or more of the line sections and still be capable of withstanding a transient disturbance. Therefore, it is evident that the line as a whole, when normally operating with all of its sections in service, must carry a load well below the non-regulated power limit.

The transient limits, both artificial limits and non-regulated limits, are shown in Fig. 2. The type of disturbance used was a single-phase line-to-neutral short-circuit applied at the receiving end by short-circuiting one transformer and line reactor. The duration of the short-circuit was varied by hand re-setting of a CO relay, (energized from the short-circuit current), and timed with a cycle counter. With a given initial load, the short-circuit was repeatedly applied for longer and longer periods, until pullout occured. Then with a lower initial load, still longer durations were used. The last before pullout and the one causing pullout are plotted for each initial load value. A positive phase sequence network was used with the voltage regulators so that no error would arise from unbalanced phase voltages.

Curve (a), Fig. 2, and curve (b), Figs. 4 and 1, were made with the same regulator adjustment, i.e., the one most favorable to transient limits. Curve (b), Fig. 2, and curve (a), of Figs. 4 and 1 were made, not with identical adjustment, but each with adjustments which were more favorable to steady-load operation. Comparison will show how the steady-load power limit must be sacrificed for best transient performance, which is, of course, more important than the steady-load performance. There can be no useful purpose served by carrying a high load under steady-state conditions, that would only be lost when a usual disturbance is encountered. Therefore it is clear that the most important performance of all is the transient power limit for a disturbance of about 30 to 60 cycle duration, which is the usual time required to clear a fault. The

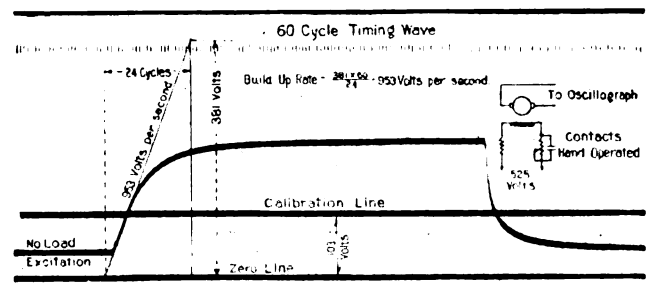


FIG. 5—AN OSCILLOGRAM OF TIME-VOLTAGE RESPONSE FOR SEPARATELY EXCITED EXCITERS

power limits for balanced-load steady-state operation, or for unbalanced-load steady-state operation with the fault hanging on, are of academic interest only.

Curves (a), (c) and (d), Fig. 2, clearly show, for the test setup, the approximate relative benefit in transient performance derived from quicker-response excitation voltages. Thus, considering a 30-cycle short-circuit, from curve (d) for non-regulated or fixed excitation, the transient power limit is 24 kw. When the 130-volt separate excitation source is used, having a speed of response of well over 200 volts per second, the limit is 44 kw, curve (c); while with 525-volt excitation, curve (a), it is 47 kw. The exciter buildup rate was determined for the 525-volt source, as shown by Fig. 5. The tangent or initial rate from no-load excitation (40 volts) was approximately 950 volts per second. The maximum voltage of the exciter was 210 volts. As stated above, the range of exciter voltage from contacts open to contacts closed was the same in all regulator tests.

The above results were obtained with a vibrating regulator which has been standard for many years. In considering commercial operating systems, these results would be affected to a certain extent by the satu-

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ration and higher time constants of actual machines, and by the higher time constants of actual composite systems, the result being to bring the curves, Fig. 2, somewhat closer together.

The relative importance of the quickness of response of the exciter, as distinguished from the regulator performance, is readily seen by comparing curves (a) and (b), Fig. 2. These curves differ only in the

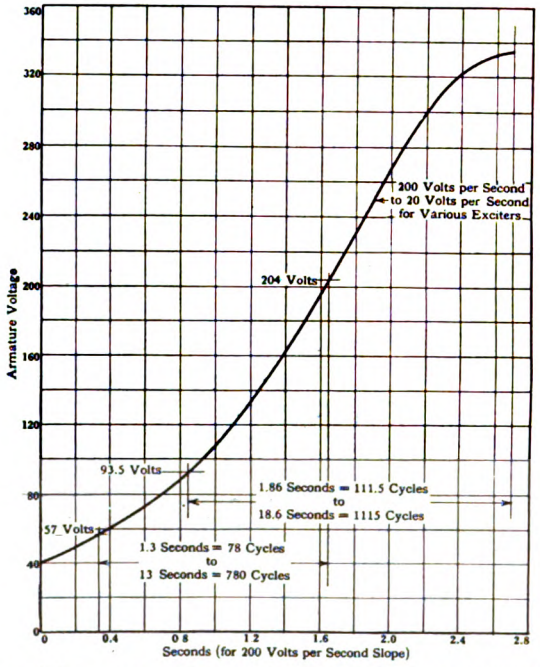


FIG. 5 (a)—A CALCULATED TIME-VOLTAGE RESPONSE CURVE FOR SELF-EXCITED EXCITERS

regulator adjustments, the quickness of response of the exciter being the same. Curve (a) is based on a regulator adjustment most favorable to transient performance for a 30 to 60 cycle short-circuit. Curve (b) is based on a different regulator adjustment whereby a higher steady-load (zero disturbance) limit is obtained. While it may be desirable to combine both characteristics, it is obviously impossible to operate normally with optimum steady-load adjustment and then, at the intsant of the fault, readjust the regulator by hand for best transient performance. As shown, curve (b) crosses curve (a) at the point corresponding to 20 cycle short-circuits. It is obvious that the region between zero and 20 cycle fault duration is of no particular interest, especially if the fault cannot be cleared in that time.

On occurrence of the fault, the regulator promptly closes its contacts and thereby momentarily loses control while the exciter is building up its voltage. Therefore, during the transient interval of 30 to 60 cycle duration, until the relays and circuit-breakers act, the more important consideration is the rate at which the exciter builds up its voltage to the required value to again give control to the regulator.

For example, Fig. 6 shows the performance of the regulator and exciter on the system of Fig. 3 when subjected to a short-circuit of 61 cycle duration. The oscillogram shows the variation in exciter armature voltage due to the normal vibration of the regulator contacts prior to the occurence of the short-circuit, after which the regulator contacts close, in this case, in about two cycles. Fig. 7 shows the regulator contacts already closed at the beginning of a five-cycle short-circuit. For the usual power system and for the more severe short-circuits, the average time required for the closing of all contacts of a number of vibrating regulators, will be about one cycle.

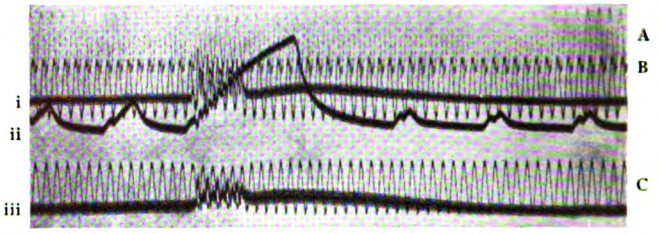


FIG. 7—OSCILLOGRAM OF LINE-TO-NEUTRAL SHORT-CIRCUIT OF 5 CYCLES DURATION AT THE MOTOR IN FIG. 3

i—Motor field current
ii—Exciter armature voltage
iii—Generator field current
A, B, C—Three phase, 60 cycle voltages

After closure of the regulator shunting contacts until they open again with the regulator in control, the exciter voltage increased from the 38.5-volt minimum to 204 volts in 29 cycles, an average of 575 volts per second. The average exciter voltage, before the fault, was approximately 57 volts. The rise from the 57-volt average to the 204-volt maximum required 27½ cycles.

Consider a slow-response standard exciter for which, as previously pointed out, the maximum response would range between 20 volts per second to 200 volts per second. Starting at a 57-volt average, see Fig. 5 (a), various exciters would require between 1.3

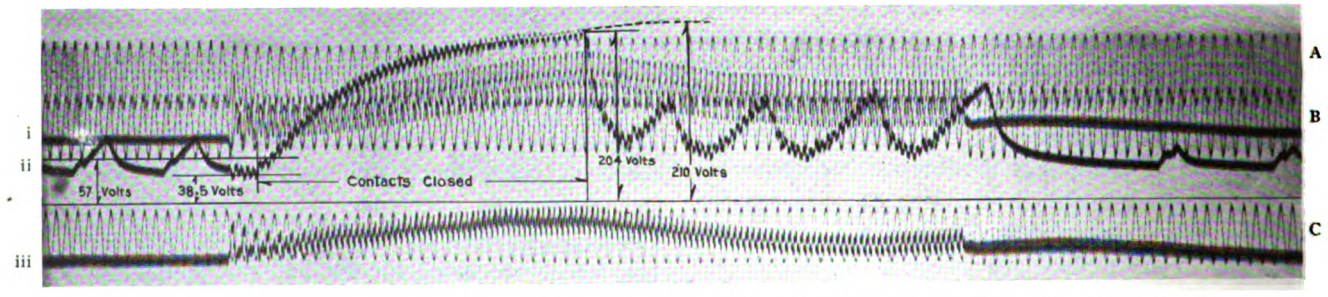


FIG. 6—OSCILLOGRAM OF LINE-TO-NEUTRAL SHORT-CIRCUIT AT THE MOTOR IN FIG. 3, 61 CYCLES DURATION

i—Motor field current
ii—Exciter armature voltage
iii—Generator field current
A, B, C—Three phase, 60 cycle voltages

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and 13 seconds to rise to 204 volts, or between 78 and 780 cycles, i.e., between 2.85 and 28.5 times as long as the separately-excited exciter response of Fig. 6. This comparison is favorable to the standard self-excited exciter because, as shown by Fig. 6, the exciter voltage increased to practically maximum, while in Fig. 5 (a) 204 volts falls far below the maximum. If the same percent of the range of Fig. 5 (a) is covered as that shown by Fig. 6, that is, 93.5 volts to 335 volts, the required time for the self-excited exciter is between 4.05 and 40.5 times as long. During such slow response, with the a-c voltage having dropped considerably, pullout would have occurred.

Therefore, it is apparent that the regulator is of less importance in transient stability problems than the rate of exciter buildup. In other words, a properly designed exciter—for systems that inherently can be benefitted thereby—is of more importance from the stability standpoint than the type of regulator, provided, of course, that the regulator possesses the proper characteristics. The most important regulator characteristics are an ability (a), to close contacts quickly and positively on the occurrence of a fault; (b), to keep its contacts closed without vibration until the required exciter voltage has been reached; (c), during the transient to resume and continue control while affected only by the positive phase sequence component of the voltage. The positive sequence voltage alone determines the synchronizing power between machines. A means for obtaining a quantity directly proportional to the positive sequence component of voltage consists of a positive sequence network. Also it is important that the control element be affected by this component of voltage to ensure correction of voltage in the proper sense. In certain types of unbalanced system faults one phase voltage temporarily rises. If the regulator were connected only to this phase without the positive sequence network, the regulator would at first cause the exciter voltage to fall instead of rise.

The selection of the type of regulator to use should thus be approached from the standpoint of the regulator itself, i.e., its ease of adjustment; sensitivity and performance during normal load conditions; ease of taking regulator in and out of control; and maintenance—as well as its operating characteristics during transients as pointed out above. The time during which the regulator is operating under transient conditions is a very small part of its total time of operation. So much so, in fact, that the adjustment and operation under normal conditions entirely determines the character and amount of maintenance required by the regulator. No adjustment for best transient operation can be tolerated which under normal operating conditions results in hunting, excessive maintenance, or burning of the contacts.

It is reasonable to conclude, therefore, that when the transient stability of a transmission system is to be improved, the points of chief interest are:—

1—What is the character and amount of maintenance required by the regulator.

2—What are the actual operating transient characteristics of the voltage regulator.

3—What speed of response is required, as determined by investigation of the system with the required performance in mind.

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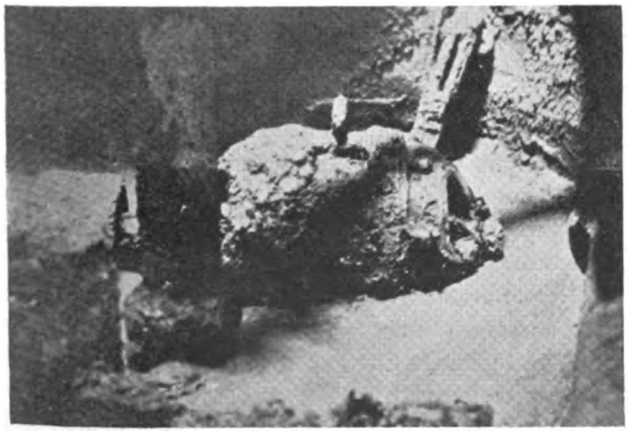
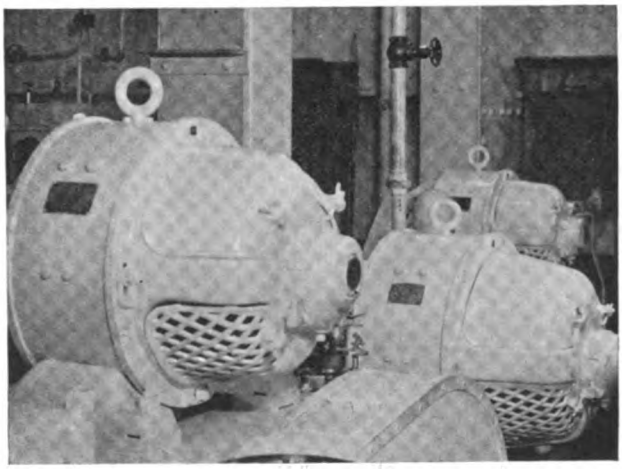
# A Study in Black and White

ELECTRIC motors may be found doing faithful duty under almost every conceivable condition—and in some conditions hardly conceivable. For instance, the plight of the motor shown on the left, though a bit unusual, is indicative of the extreme conditions in which motors are sometimes found. That a motor will continue to run under such conditions stands proof of its sturdiness (seaworthines we were tempted to say). In this particular case, through the failure of a pump gasket, a squirrel-cage motor, operating in a pit, was completely submerged in a mixture of ground limestone and water. The motor continued to operate until disconnected by the overload relay in the control circuit. The slurry was removed from the pit, the gasket repaired, and the motor put back in operation with no other attention than a thorough washing. The sleeve bearing being thoroughly and effectively sealed, no slurry entered the bearing housing and a renewal of the lubricant was unnecessary.





In forceful contrast with this is the immaculate conditions of the three motors in the picture to the right. These three motors are white enameled and are giving good service on the motorship *Challenger*.

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# Graphical Flux Mapping

## VI.—Direct-Current Railway Motor—Salient Pole Synchronous Machine—Universal Motor—Directional Element of a Reverse-Current Relay—Three-Pole Magnetic Contactor.

J. F. CALVERT and A. M. HARRISON

In the article in the JOURNAL for August, 1928, representative flux distributions were shown for direct-current motors and generators. The present article illustrates certain fields in a number of types of apparatus, both rotating and stationary. In most cases, no attempt is made to show all types of flux fields for each machine.

### SALIENT-POLE SYNCHRONOUS MACHINES

The flux distribution in the air-gap and interpolar space of a salient-pole synchronous machine is shown in Fig. 50. No detailed description is needed of this case, as similar fields have been previously discussed.

The approximate flux distribution in the radial plane through the center of the pole of a salient-pole alternator is shown in Fig. 51. Only the rotor winding is excited. This drawing is predicated on the same general assumptions as have been all end-zone flux maps shown in these articles. That is, the field is plotted by assuming an incremental section of uniform depth perpendicular to the plane of the drawing, thus reducing the mapping to a strictly two dimensional problem. In reality, the boundaries of the flux tubes are nearer this center plane in the neighborhood of the air-gap, and diverge with increasing radial distance from the shaft centerline. Probably the most important reason for this is that there is an m.m.f. difference between poles as well as between the pole and the stator.

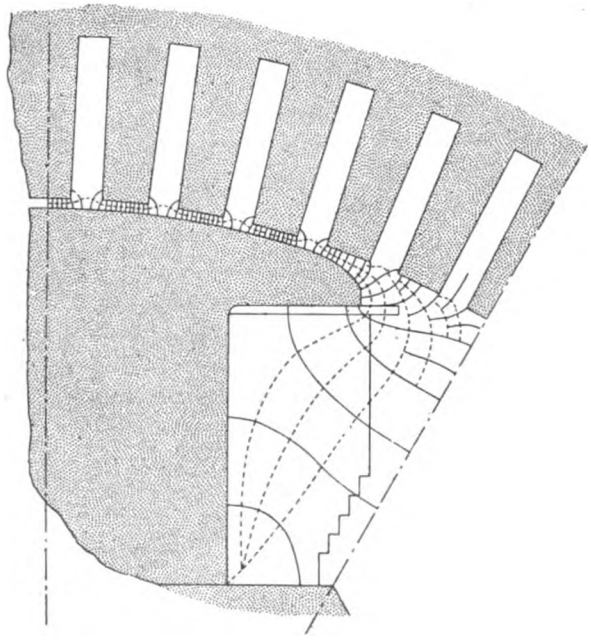

FIG. 50—AIR-GAP AND INTERPOLAR FIELDS OF A SALIENT-POLE SYNCHRONOUS MACHINE
With only the rotor winding excited.

In order to approximate the true field more nearly, one should allow for a variation in the depth of the flux sheet in the direction perpendicular to the plane of the drawing. A correction of this sort has been made in certain cases and the resulting field checked with a fair degree of accuracy by comparing the measured with the calculated inductances of the coils. However, the first step in such an approximation is to draw the field as shown in Fig. 51. In the latter, the general directions of the flux lines are quite similar to those in the real case, but the distribution or spacing of the ampere-turn lines is not. Even the approximate field, based upon uniform depth perpendicular to the plane of the paper, is not an easy figure to draw. It is advisable to take certain measures as aids in the field mapping.

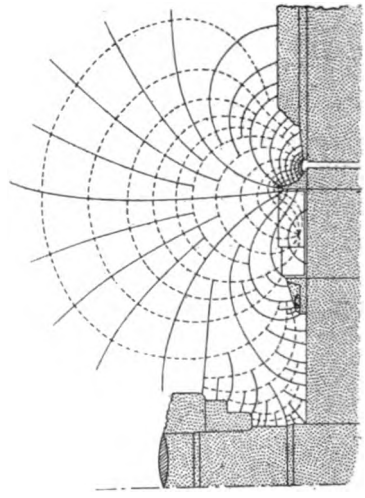

FIG. 51—END-ZONE FIELD OF A SALIENT-POLE SYNCHRONOUS MACHINE
With only the rotor winding excited.

It is evident from a brief consideration of the main magnetic circuit that the ampere-turn lines must emanate from an m.m.f. center in the field coil side at one end of the pole, pass through the air-gap (assuming no saturation) and converge at a similar center in the coil side at the other end of the pole. Briefly, the ampere-turn lines must begin and end at m.m.f. centers within the conductors, and the full m.m.f. per pole must be effective in the air-gap. It is possible to start these ampere-turn lines outward from the air-gap, and to plot the flux lines for a certain distance from there, so long as the distribution is predominantly affected by the iron. Also, it is possible to make a preliminary

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guess as to the location of the m.m.f. center in the field copper, and to start the same number of lines from there as were brought out from the air-gap. Finally, these ampere-turn lines must be joined as shown in Fig. 51.

There is a certain graphic similarity between this field and that which would exist if two conductors carrying equal currents in opposite directions were placed near an iron surface. Suppose that one were to occupy the position of the m.m.f. center in the field

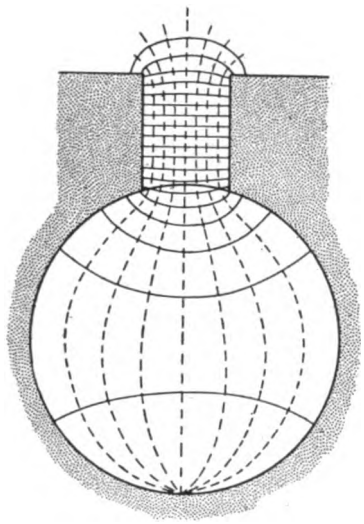

FIG. 52—FIELD OF A ROUND DAMPER BAR ON A SALIENT-POLE SYNCHRONOUS MACHINE
Assuming uniform current distribution.

coil, and the other were to replace the effect of the air-gap where the ampere-turn lines converge nearly to a point. With this idea in mind, it becomes easier to plot the field away from the iron parts. Large curvilinear squares should be roughed in at first. The general direction of the field in the corner between the shaft and the rotor body can be estimated by an auxiliary sketch in this sector.

The location of the m.m.f. center must be adjusted to give the proper relations between ampere-turns and reluctance within the copper as well as outside[1]. Eventually, the whole field must be balanced for accuracy.

In Fig. 52 is shown the field of a round damper bar of a type commonly used in salient-pole synchronous motors. It is drawn on the basis of uniform current distributions in the copper and on the assumption that the bar completely fills the slot.

The field is started in the slot at the top. Obviously, the mid-ampere-turn line must be projected straight downward into the conductor. The other orthogonal lines can be made to curve around the corners upon entrance into the slot and to cut practically unit permeances from equal flux tubes, because there has been only slight reduction in the copper. The work must then be carried downward into the copper by estimating the amount of copper remaining between the ampere-turn lines from the amount already passed by. The fundamental relations between reluctance and copper area, (given in the first article) must be fulfilled in this case. It is found that, for a round bar, when the copper is in direct contact with the iron, the m.m.f. center is right on the iron at the bottom of the slot on the vertical center line.

[1]See first article of this series in the JOURNAL for March 1928.

### THE INTERPOLAR FIELD OF A DIRECT-CURRENT RAILWAY MOTOR

The flux distribution established in a direct-current railway motor when only the main pole winding is excited is shown in Fig. 53. It is drawn in much the same manner as the fields of other salient-pole machines. The flux in the air-gap is plotted and the flux and ampere-turn fields extrapolated so as to round the tip of the main pole with a continuous array of curvilinear squares. From here, the ampere-turn lines are carried toward the conductor, and the field plotted as in any irregularly shaped slot. Further, elaborations on the plotting methods are unnecessary, since the fields of direct-current motors and generators have been shown in some detail in a previous article of this series[2].

It can be shown by methods developed by Th. Lehman[3] that saturation has a negligible effect on the general shape of the interpolar field. In using this type of field to calculate (a) the field form; or (b) the saturation of the stator iron parts; it is best to simplify the drawing by replacing the slotted rotor diameter with a smooth cylindrical surface of a slightly

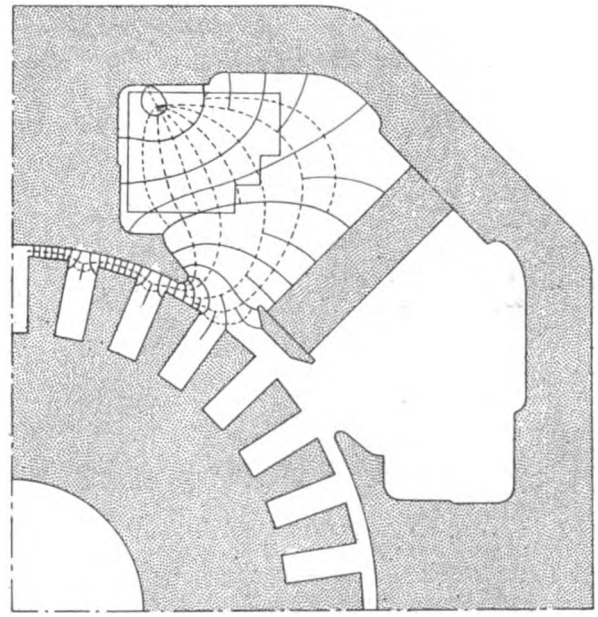

FIG. 53—AIR-GAP AND INTERPOLAR FIELD OF A DIRECT-CURRENT RAILWAY MOTOR
With only the main pole winding excited.

smaller diameter. The latter rotor surface should give very nearly the same average reluctance as the former. The mechanical air-gap is simply increased in accordance with Carter's coefficient when calculated for the rotor slotting.

[2]In the JOURNAL for August 1928.

[3]"Determination of Partial and Resultant Magnetic Fields in Saturated Dynamos" by Th. Lehman, *Revue General d'Electricite*, December 24, 1927, pp. 1105-1119.

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The methods of plotting the flux fields (a) due only to the commutating-pole winding, (b) due only to the armature winding, and (c) due to the main pole, commutating pole, and armature windings excited at the same time, have been discussed in the previous article for certain direct-current machines. These fields will not be shown here for the railway motor, but could be plotted in corresponding manners.

### THE FLUX DISTRIBUTION IN A UNIVERSAL MOTOR

The flux conditions in a universal motor, when only the main pole or stator winding is excited, are shown in Fig. 54. To plot the fields shown in this figure, it is assumed first that there is no saturation in the iron. The air-gap flux is drawn and the work carried around the pole tip and toward the center line between poles. The latter line is orthogonal to the flux field. The field is mapped in the stator winding, and the center located by trial and error until the elementary principles concerning the ampere-turns and reluctance have been satisfied.

This procedure gives a distribution for the flux at both the stator and rotor iron surfaces. If the flux distribution is assumed to be symmetrical about the pole center line, and if it is assumed that no flux leaves the back of the stator, then the ampere-turn lines must meet perpendicularly with the pole center line and the outer edge of the stator iron. Thus, all the boundary conditions for the stator have been fixed. Now, if uniform permeability is assumed for the iron, the arrangement of equal flux tubes and of equal ampere-

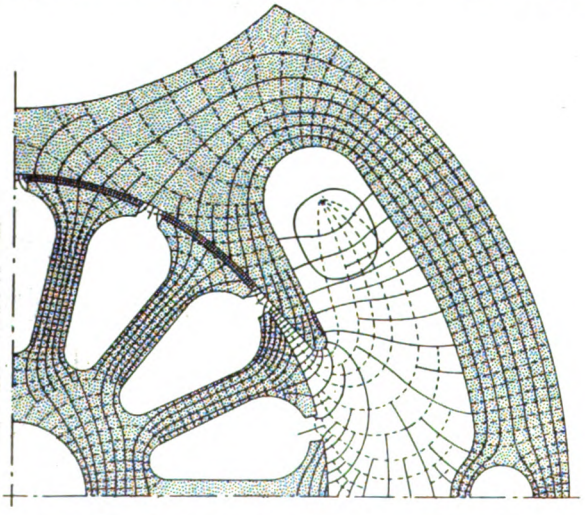

FIG. 54—FLUX DISTRIBUTION OF A UNIVERSAL MOTOR
With only the stator winding excited and on the basis of uniform permeability in the iron.

turn lines must be such as to divide the whole field into curvilinear squares as shown.

The flux field within the rotor iron has been plotted in a similar manner. When the rotor is turning, the eddy currents in the shaft will prevent the flux from penetrating more than about one-eighth of an inch. It has been assumed in making the drawing that none of the main flux entered the shaft.

### FLUX DISTRIBUTIONS IN THE DIRECTIONAL ELEMENT OF A REVERSE-CURRENT RELAY

In Figs. 55, 56, and 57, the flux distributions are shown for the directional element of a reverse-current relay. In Fig. 55, it is assumed that only the lower winding is excited, and in such a direction that the upper end of the central pole is the north pole.

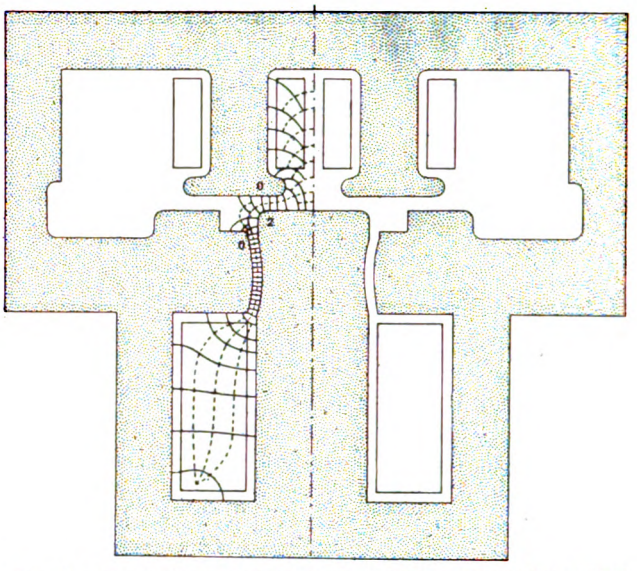

FIG. 55—DIRECTIONAL ELEMENT OF A REVERSE-CURRENT RELAY
With only the lower winding excited.

This field may be conveniently started at the vertical gap between the central pole and the surrounding iron structure, because it is known that the flux lines must lie almost straight across this gap. From here, the field may be extended toward the upper poles. All of the ampere-turn lines must emanate from an m.m.f. center in the lower conductor on the left, pass over the top of the lower pole, and converge at the corresponding center in the right hand side of the lower coil.

There will be a distribution of flux in the space between the two upper poles similar to that which has been illustrated in previous articles for the flux in the slots adjacent to the air-gap. A similar type of distribution must obtain in the upper air spaces on the sides. However, the densities here are so low that these fields have not been illustrated.

Starting again at the gap on the left, the flux mapping may now be extended downward into the lower conductor, which contains one m.m.f. center of the excited coil. With a chosen number of ampere-turn lines entering this space, the field distribution can be easily estimated near the top of the conductor, because at first there is no great reduction in the ampere-turns between orthogonal lines. The orthogonal lines can be made to cut nearly unit permeances from equal flux tubes; only slight modifications are required to make the distribution practically correct. By proceeding in this manner, the mid-ampere-turn line is found almost to coincide with the vertical center line of the coil by the time it has turned definitely downward into the copper. Yet this mid-ampere-turn line must proceed

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to the m.m.f. center, join with the one orthogonal line which goes to the iron, and these two must bisect the copper area. The other two orthogonal lines which were started in near the top must each bisect the remaining halves of the conductor as shown. In order to fulfill the principles for plotting within the conductor, it seems that the m.m.f. center must be shifted to

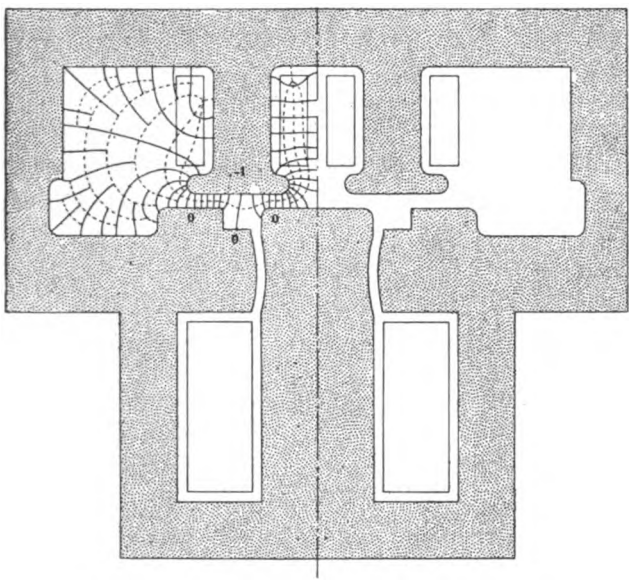


FIG. 56—DIRECTIONAL ELEMENT OF A REVERSE-CURRENT RELAY
With only the upper winding excited.

the left near the bottom, as the point of entrance of the ampere-turn or orthogonal lines is shifted to the right at the top.

In Fig. 56, it is assumed that the upper two poles of the directional element are excited, the left one as a south pole and the right one as a north pole. The numbering on the pole surface and the adjacent iron parts is such that the difference in the numbers show the relative differences in the m.m.f.'s in the directions from the higher toward the lower numbers, as 0 to — 1. The same sort of notation is used as in Fig. 55.

The m.m.f. and flux conditions are symmetrical about the center line between the two poles, so that flux must cross this line at right angles, and all the ampere-turn lines from the m.m.f. center in the con-

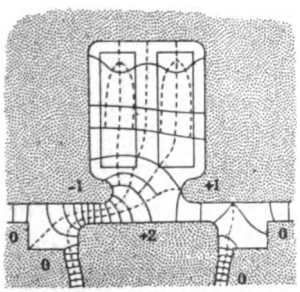


FIG. 57—DIRECTIONAL ELEMENT OF A REVERSE-CURRENT RELAY
With each element excited as shown by preceding figures.

ductor on one side of a pole must converge at the m.m.f. center in the same coil on the other side of the same pole.

The plotting of air-gap and commutating-pole fields have been described before in a number of instances. The only difference between Fig. 56 and drawings of other salient pole fields is that the right and left hand sides of each pole are dissimilar, and it is necessary to draw both sides of one pole in order to establish the complete field.

In Fig. 57 is illustrated the flux field between the poles of the directional element at the instant of time when the magnitude of the m.m.f. in the lower coil is equal to the combined value of the two upper pole windings in series. It is simply the distribution which would be obtained if the two preceding figures were superposed. In fact, it will be seen that the numbers on the pole surfaces in the two preceding figures have been superposed to obtain those in Fig. 57. Since the differences in these numbers represent the ampere-turns between these surfaces in the direction from the higher toward the lower numbers, and as these ampere-turn lines do not cross, it is easy to establish from which conductors these lines must emanate, and then to complete the drawing as shown.

### MAGNETIC CONTACTOR

A rather difficult type of field to balance is shown in Fig. 58. Obviously, the amount of flux which crosses the central gap from the lower to the upper iron element must return in the outer gaps. To be more exact, the flux is crossing from the lower to the upper element between the two singular points on the upper member, and is leaving the upper element from all the rest of the surface on the upper element to return to the lower one. It is necessary, then, to make a preliminary estimate of the reluctances of these three gaps in order to approximate the division of ampere-turns between the three air-gaps.

With this as a start, the ampere turns are divided, and the chosen number of ampere-turn lines allotted to each gap. The field mapping probably should be started in the gaps first, and worked outward beyond the magnet, and in toward the conductors. The fields outside of the iron members are relatively easy to plot.

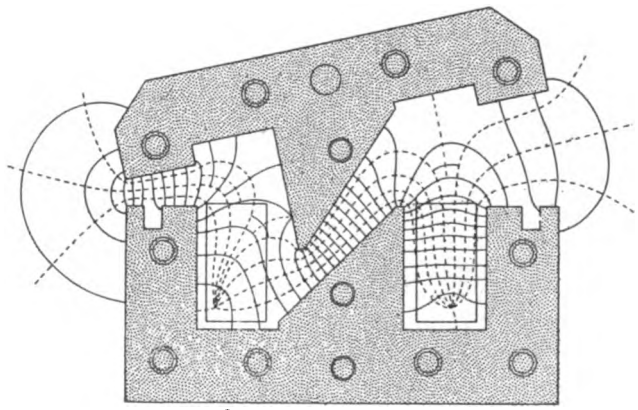

FIG. 58—MAGNETIC CONTACTOR
With one winding excited as shown.

The conductor on the right is rather symmetrically located and offers a fairly simple slot field to draw. However, the left-hand conductor requires a good deal of effort to balance. In the final analysis, this field must not only appear to be correct throughout, so far as the accuracy of the curvilinear squares is concerned, but the amount of flux from one member to the other must equal the amount returning.

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# Making the Small Turbine Safe

C. L. SOUTHMAYD
Engineering Dept., South Phila. Works
Westinghouse Electric & Mfg. Co.

SAFETY of operation is the most important requirement of prime mover apparatus for central station and industrial plant service. Modern practice not only demands that a machine be capable of reliable and efficient service but that this service be secured without danger to the operators. Excessive overspeeding is the most common cause of small turbine wrecks. The most complete assurance that may be had of safe operation is the provision of reliable means of governing the turbine speed. It is said that safety and reliability go hand in hand and perhaps no better proof of this statement may be found than in the design of small turbine governors. The manufacturers have constantly endeavored to perfect the governing mechanisms and, as a result, small turbines today are not only much more reliable, but also insure much greater safety of operation.

Small turbines are commonly provided with two speed-governing devices, the main or speed regulating governor and an emergency overspeed governor. The main governor serves to maintain a constant operating speed over all ranges of load by controlling the amount of steam admitted to the turbine. The emergency overspeed governor serves to operate a quick-closing valve in the admission line, should the unit reach some predetermined overspeed, due to failure of the main governor.

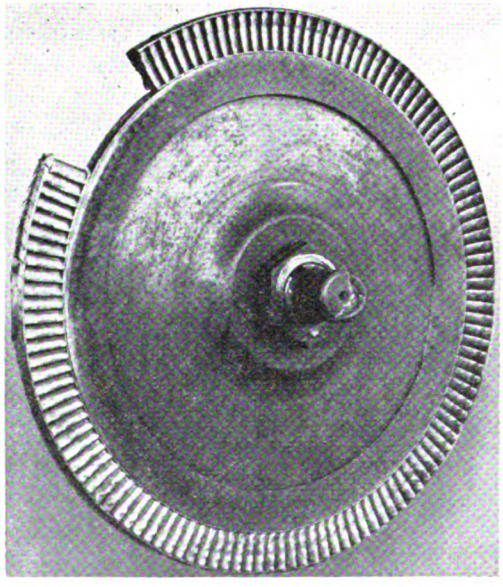

FIG. 1—TURBINE ROTOR AFTER THE OVERSPEED TEST
Showing that the safety blade came out and created an unbalance. Evidence of the braking action is seen on the end of the shaft and at the periphery of the rotor.

Most small turbines are provided with a fly-ball type main governor. This governor may be either of the high-speed type, mounted horizontally on the rotor shaft or of the slow-speed, gear-driven vertical type. The majority of these governors are directly connected to the admission valves, although on some of the larger capacity machines, the governors serve to actuate an oil relay, which in turn, controls the action of the admission valves.

There has lately been incorporated on small turbines, an oil impeller-type governing system similar to

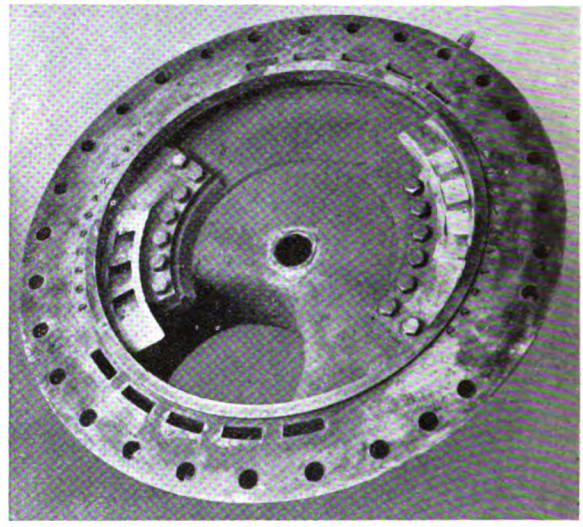

FIG. 2—THE TURBINE CYLINDER AFTER THE OVERSPEED TEST
Showing evidence of wear corresponding to the points of wear on rotor shaft.

that used on larger turbines. This system consists of a spring-loaded piston, directly connected to the admission valve and actuated by high-pressure oil from an impeller-type pump located on the rotor shaft. The discharge pressure of this oil varies as the square of the speed, and this characteristic is utilized to produce a very sensitive, reliable and positive means of controlling the operating speed.

The emergency overspeed governor is of simple, reliable, and efficient design and when properly adjusted, insures positive protection against excessive overspeeds caused by failure of the main governor to control properly the admission of steam to the turbine. This mechanism consists, in essentials, of a spring loaded plunger that flies out when the turbine reaches a predetermined speed, releasing a heavy weight which, in falling, trips out the throttle, shutting off the steam supply to the turbine. The falling weight insures a positive action of the throttle trip and the device has the added feature that the throttle cannot be opened until the emergency overspeed governor is reset.

These two governing systems constitute as nearly perfect a system of speed control as it has been thus far possible to provide, but no device, no matter how

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well designed and constructed, can be expected to function unless properly maintained. There are also conditions over which the two systems of protection usually incorporated have no control, such as the motorizing of a direct-current generator being driven by the turbine. Instances have also been known of foreign matter in the steam so pitting the governor valves and throttle valve seats that even though both the main

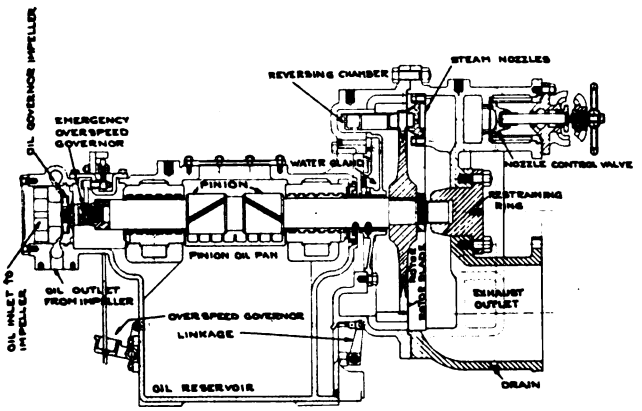


FIG. 3—SECTION OF A SMALL, GEARED TURBINE FITTED WITH SAFETY BLADES AND RESTRAINING RING

governor and the throttle valves were closed, sufficient steam was admitted to the turbine to increase the speed to the point of destruction.

Large turbines, by virtue of their importance in the power plant are usually well maintained and the governor and overspeed devices kept in good working order. Small turbines, on the other hand, are often treated as of less importance and, if they provide uninterrupted service, usually receive little attention other than that needed to insure continued operation. In this event, the emergency device may become inoperative and may fail when needed. It is also possible that through some error, the emergency overspeed device may be incorrectly set, in which event the chance for overspeeding is also increased.

In order that a maximum degree of safety may be had in small turbine operation without any impairment of reliability, an additional protection against excessive overspeeding has been developed which utilizes a restraining ring. The principle of the restraining ring is to provide some means whereby the rotating element of the turbine, on reaching a sufficient amount of overspeed, will become unbalanced and, as a result, will deflect a small amount and rub on some suitable surface. This rubbing results in a braking action which serves to keep the speed of the rotating element below the point of rupture.

The restraining ring proper consists of either a heavy steel ring securely fastened to the inside of the cylinder or an especially reinforced section of the cylinder itself, or both. This ring fits around the rotating element of the turbine with a close clearance, ample to insure frictionless operation under normal conditions but sufficiently close to necessitate only a small deflection of the rotor for the braking action to take place.

The unbalance of the rotor, necessary to produce this deflection, is secured by fastening two of the blades, termed "safety blades", in such a manner that they will come out should the rotor reach a speed approximating twice normal operating speed. These two safety blades are located 120 degrees apart on the periphery of the rotor so that the proper amount of unbalance is secured if either or both come out and they are pinned with a material of somewhat lower shearing strength than the remainder of the blades.

All danger of disc rupture is eliminated as the fastening of the two safety blades constitutes the weakest part of the rotor assembly when subject to high centrifugal stress. The two blades are of such a relatively small mass that they cause no damage to the rotor or cylinder when they come out and merely fall to the bottom of the cylinder. The rotor is so held in place by the restraining rings that it is impossible for it to deflect an amount sufficient to cause breakage of the shaft.

The damage resulting from the overspeeding or "running away" of a turbine fitted with restraining rings is confined to the inside of the cylinder; the danger to the operators is nil and that to property negligible. The cost of re-conditioning a turbine that is so provided and that has overspeeded will consist of replacing the two safety blades, rebabbitting the rotor shaft bearings and dressing up the parts rubbed. Thus it may be seen that the cost of reconditioning such a turbine is negligible compared with the possible cost of the damage resulting from the wreck of a turbine not equipped with this safety feature.

This restraining ring principle was not incorporated in small turbines until the practicability of the

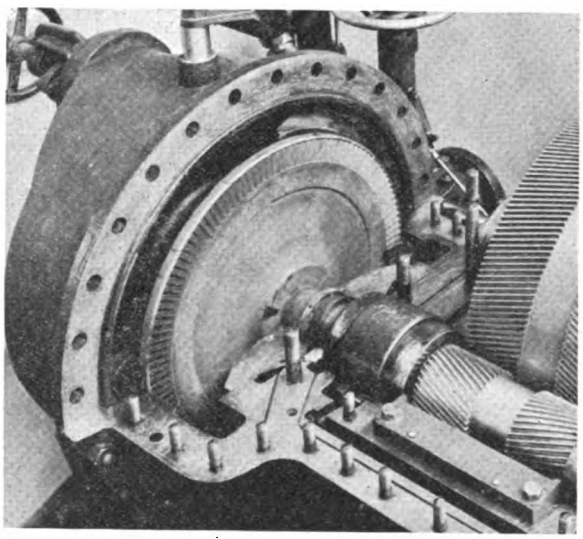

FIG. 4—INTERIOR VIEW OF THE TURBINE IN FIG. 3

feature had been proven by exhaustive tests. Among the most important of these tests and the one which furnished the most significant results was the so-called "destruction test". The turbine to be tested was erected on a test pit complete with the exception of the governor and emergency overspeed device which were left

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off in order that the restraining ring might operate under the same conditions as it would should the governing devices become inoperative.

The turbine was then covered with sand bags and the whole was encased in a "log house" made of heavy 8 by 12 inch timbers mortised together. This log house was then covered with a roof made of ½ inch boiler plate which, in turn, was covered with several layers of sand bags. Provision was made to control the flow of steam to the turbine from a point some twenty feet away and the steam line was additionally braced so that should it become broken or cut-off, the escaping steam could not blow in the direction of the observers. Arrangements were also made to measure the turbine speed at a distance.

After the preparations had been completed, the valve in the steam admission line was opened wide and the results noted. The turbine, designed for a normal speed of 7200 r.p.m., unhampered by a governor, overspeed device or load, quickly gained in speed. At a speed of approximately 11 400 r.p.m., the two safety blades were heard to come out, to be followed immediately by the sound of the rotor rubbing in the restraining rings. This rubbing or braking action resulted in a marked decrease in the speed which continued until the rotor cleared itself. On clearing itself, it again gained in speed only to rub again and another decrease in speed resulted. This process was allowed to repeat itself several times before the steam was turned off.

The turbine, when uncovered, showed no external evidence of damage. The turbine cylinder was not cracked and there were no signs of abnormal operation. The turbine cylinder cover was then removed and the damage visible was sufficient proof of the adequacy of the restraining ring feature. Figs. 1 and 2 are views taken of the turbine after the test and show the extent of the damage. There was evidence of rubbing at the periphery of the rotor, at the end of the rotor shaft, and at corresponding points in the turbine cylinder.

Proof of the dependability of this safety feature in actual service is provided by the case of a turbine-driven lighting set that overspeeded on board a ship at sea. The restraining rings acted to prevent the speed becoming excessive and the damage resulting was slight. A blade was removed from the rotor opposite the point where the safety blade had come out in order to balance the rotor and the ship entered port with the set in service.

Fig. 3 is a cross-section of a small, single-rotor, re-entry-type turbine adapted for generator drives through a reduction gear. Fig. 4 shows the interior of the same type turbine. The restraining ring is an integral part of the turbine and not a separate device, therefore, it cannot be removed, misadjusted or become inoperative under any condition.

The restraining ring, while insuring adequate protection against destructive overspeeds, is intended solely as a last resource in the event that both the main governor and emergency overspeed governor should fail, and the presence of such a feature should not warrant any neglect on the part of the operator in not maintaining the two principal speed-governing devices The restraining ring does not prevent damage due to overspeeding but it does limit the extent of such damage to the interior of the turbine and insures safety to human life at all times.

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# Methods of Testing Electrical Apparatus

## XXVII--Temperature Tests

THE object of the temperature test is to determine the temperature rise of the apparatus under specified load conditions. There are several methods of making this test, all of which are intended to approximate as nearly as possible the operating conditions insofar as temperature is concerned. The best might be to run under actual load conditions by loading into water rheostats or other apparatus capable of dissipating the electrical energy. This method requires considerable power and is expensive, therefore, it is seldom used, and then only when the units to be tested are of low kv-a rating.

When two or more transformers of the same design are available, they can be artificially loaded by what is commonly known as the loading back method, in which both transformers are subjected to approximately their rated load condition, and the power required is only that necessary to supply the losses. The scheme of connections generally employed in making this test is shown in Fig. 123. The low-voltage windings are connected to the source of supply, thereby, as a safety precaution, confining the high-voltage circuit to the transformers on test. It is not essential to magnetize and load the transformers from the same phase, as shown. Different phases of a polyphase circuit, or separate generators may be used but, in all cases, the frequency of the circuits should be the same as the rated frequency of the transformers on test. If it is found impossible to supply either the magnetizing voltage or the load current at the rated frequency, then such values of voltage or current must be used at the substitute frequency as will cause the same losses that occur at rated frequency.

If it is found necessary to circulate the load current in the high-voltage winding, and the high-voltage winding is purposely grounded in order to protect the

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loading transformer from undue voltage strain to ground, then the low-voltage winding also must be grounded, as there may be a dangerous difference of potential between it and ground.

As the method of loading single-phase transformers just described is applicable only when there are two or more similar units to be tested, some other method must be used when only a single unit is available. Several methods have been devised to meet such a condition, some of which are shown in Fig. 124, 125, and 126.

The method shown in Fig. 124, commonly called opposed halves, is applicable to any single-phase transformer if the respective high and low-voltage windings can be separated into two equal parts and the coil assembly is such as provides the necessary insulation between adjacent high-voltage groups. In this method, two separate supply transformers are required, otherwise, the test is practically the same as the two transformer loading back method. However, if the unit to be tested happens to be a large capacity, low-voltage transformer, the load losses under this condition may

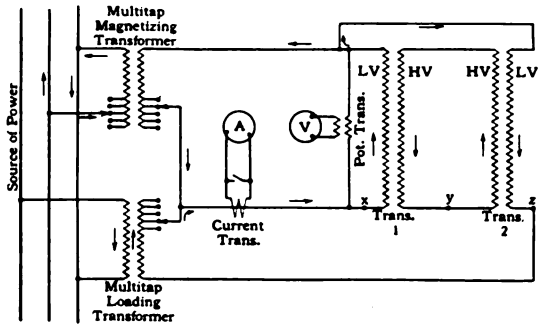


FIG. 123—CONNECTIONS USED IN LOADING TRANSFORMERS FOR TEMPERATURE TEST

be somewhat greater than normal on account of the abnormal impedance condition.

The scheme of connections, shown in Fig. 124, is applicable only to core type transformers in which the windings are not cross connected. The impedance of the transformer is such as to give practically normal current in both high-voltage and low-voltage windings.

When applying the methods, shown in Fig. 124 or 125, large stray fields are produced which may cause extra losses in the windings and frame work of the transformer. In order to compensate for these losses, wattmeters should be placed in the loading circuits and the currents adjusted to such a value as will give a total loss equal to the copper loss measured in the standard way and these values of current should be used during the temperature run.

When it is impossible to apply any of the foregoing methods, the alternate open-circuit and short-circuit method may be employed, which is carried out as follows:—The transformer is first run on open circuit at a voltage which will produce a core loss equal in value to the sum of the normal core and copper losses for a fraction of a given period, the fraction being equal to the ratio of the normal core loss to the total loss. Next, the transformer is run on short-circuit with currents in the windings of such value as to give a short-circuit loss equal to the total loss, for the remainder of the period, which is a fraction of the total period, equal to the ratio of the normal copper loss to the total loss. The cycle is repeated until constant temperature conditions are attained. With a length of

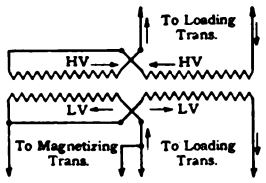


FIG. 124—CONNECTIONS SOMETIMES USED FOR LOADING ONE SINGLE-PHASE SHELL-TYPE TRANSFORMER

period not too great, this method will give results closely approximating those obtained by the loading back method.

As temperature tests are generally run until constant temperature conditions are attained, it is permissible, in order to save time, to begin the test with hot oil or to operate the transformers under abnormal conditions until the contemplated constant temperature is approached. Transformers designed for 25 cycle service may be started at 160 percent rated load current and 100 percent of normal voltage, those for 50 or 60 cycles at 150 percent load current and 110 percent of normal voltage. Under these conditions, the time required to reach approximately constant temperature may be from six to eight hours, depending upon the size of the apparatus and the specified temperature limits. If the specified temperature rise limit is 55 degrees C., measured by the increase in resistance method, the load current and the voltage should be changed to normal when the temperature of the oil, as indicated by thermometer, is 45 degrees C. above the ambient temperature. If the limit is 50 degrees C., change at 38 degrees C. oil rise and if 40 degrees C., when at approximately 32 degrees C. oil rise. The test should then be continued until the oil temperature does not vary more than one degree C., and the corresponding room temperature not more than one and one-half degrees C. in three hours. The total time occupied in making the test may be from ten to fourteen hours.

### PROCEDURE FOR TEMPERATURE TEST BY LOADING BACK METHOD

To make the temperature test by the loading back method set the transformers in position, as previously* outlined. If they are equipped with temperature indicating devices, such as resistance elements inbedded in heating coils, Foxboro thermometers or thermocouples, see that such devices are properly located during the setting up period. The temperature indicating devices for determining the oil and ambient temperatures should also be arranged prior to applying power to the transformer. The oil temperature is determined by a thermocouple placed two inches below the surface

*In the JOURNAL for Aug. 1928, p. 410.

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of the oil in the vertical center line of the case. When the current values of the outgoing leads are in excess of 2000 amperes, temperature readings should be taken of the leads and also of that part of case or cover in proximity to the outgoing leads. The ambient temperature is determined by several thermometers placed

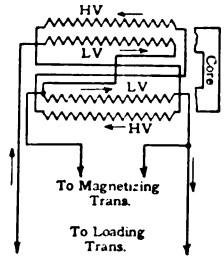


FIG. 125—CONNECTIONS SOMETIMES USED FOR LOADING ONE SINGLE-PHASE CORE-TYPE TRANSFORMER

from three to six feet away from the transformers and approximately four feet above the floor line. Connect the test wiring according to the scheme shown in Fig. 123, or its equivalent whichever is best.

The cold resistance, which will be used as a base in computing the final temperature at the end of the run, should now be measured. Disconnect the test wiring at the points *x*, *y*, and *z*, Fig. 123. Connect the resistance measuring lines directly to the terminals of the respective windings to be measured at such points as can be easily duplicated when measuring the hot resistance.

There is no definite rule for the order in which the cold resistances of the respective windings are to be taken. However, it is essential that a definite plan be followed when measuring the hot resistances in order that the measurement may be taken both rapidly and accurately. The usual order is,—first, measure the low-voltage winding of one unit, then the high-voltage winding of the same unit; next the high-voltage winding of the other unit, and then, its low-voltage winding. Be careful to maintain the same relative polarity with regard to the bridge leads and the transformer leads, when changing the bridge leads from the low-voltage to the high-voltage winding or vice versa. This precaution will prevent reversing the residual magnetism in the transformer core, and, consequently, will lessen the time required for the direct current to reach a constant value. Determine the temperature of the windings in the same manner as described previously*. Record all measured values and the corresponding winding temperature on the temperature test sheet.

Before applying power for the temperature test, be sure that all connections are properly made and also that the loading and magnetizing transformers have ample capacity. The kv-a required to load two transformers at their normal rating will be twice the normal impedance volt-amperes of one unit, and the kv-a to magnetize will be approximately the sum of the exciting volt-amperes (apparent watts) of the two units.

Assuming that the test is to be started at 150 per-

*In the JOURNAL for Aug. 1928, p. 410.

cent of normal rated current, the kv-a required to load will be four and one-half times the normal impedance volt-amperes of one unit, and the kv-a to magnetize at 110 percent or 120 percent of normal voltage, will be from three to five times the normal exciting volt-amperes of one unit. Full voltage should not be applied suddenly if the transformers are of a relatively large kv-a rating, and especially if designed for 25 cycle service, as there may be a severe rush of current at the instant of switching. While the surge may not be detrimental to the transformers being tested, it may be sufficient to cause damage to the testing equipment, particularly to an induction-type regulator in case one is being used. For the same reason, ammeters should be short-circuited by a suitable switch before applying the magnetizing voltage.

Set the switch combination of the loading transformer to give a low secondary voltage and then close the power switch, thereby applying a low voltage to the transformers on test. Note the value of the load current and if it is commensurate with the voltage applied, gradually increase it until the desired value is reached. The magnetizing transformer should be connected to deliver a low value of secondary voltage, and the switch connecting it to the power circuit closed. If the indications are satisfactory, gradually increase the voltage until the desired value is reached.

To determine the relative directions of the loading and exciting currents, readings of the load ammeter should be taken immediately before and after the magnetizing voltage is applied. If the latter indication is greater than the former, the direction is correct; if less, it is incorrect and the power switch should be opened and the magnetizing transformer connected to another phase of the same source. Observations of load current, magnetizing voltage and all temperature indicators, used in connection with the test, should be made

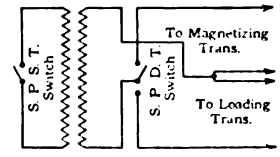


FIG. 126—CONNECTIONS FOR ALTERNATE OPEN-CIRCUIT, SHORT-CIRCUIT TEMPERATURE RUN ON ONE SINGLE-PHASE TRANSFORMER

at frequent intervals during the heating up period, but need not be recorded.

When the temperature rise of the oil has reached the proper value, the load current and magnetizing voltage should be adjusted to the specified values of the test. The test should then be continued until steady temperature conditions have been reached. Readings of all temperature indicating devices and meters should be taken and recorded on the temperature test sheets each half hour.

Preparatory to taking the hot resistance measurements, the resistance measuring outfit should be placed convenient to both transformers, the ratio and resistance arms of the bridge set in anticipation of their

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approximate values, and all preparations made to carry out the test as rapidly as is consistent with accuracy. A sufficient number of men should be at hand, and at the proper time the one in charge gives the order to open the power switches (loading and magnetizing), the temporary wiring should then be disconnected at the points *x*, *y* and *z* of Fig. 123. Connect the resistance measuring lines to the terminals of the respective windings at the same points used when the cold resistances were measured. Record the time that has elapsed between the instant of the removal of the load and the time of taking each resistance reading. The elapsed time for the last resistance reading should not exceed four minutes.

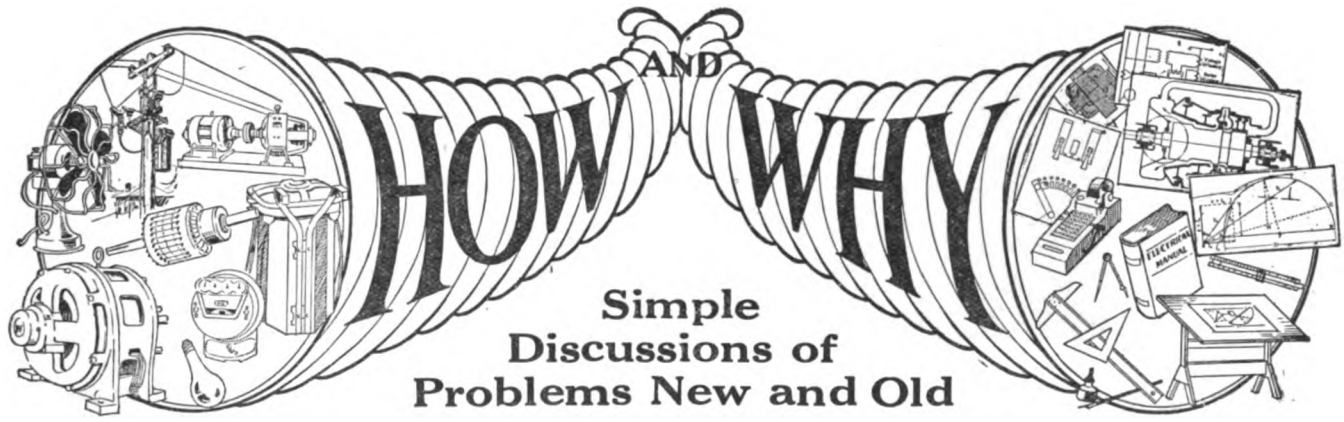
As soon as all resistance measurements have been completed, the transformers should be re-connected and the test resumed under the same conditions as before so that no time will be lost in case check measurements of resistance are required.

The temperature rise should be calculated by the increase in resistance method, as follows:—

Let $Rt$ = the cold resistance at $t$ degrees C.
$Rt'$ = the hot resistance at the winding temperature of $t'$ degrees C.
$t_a$ = the ambient temperature at the time of measuring $Rt'$.
Then, $t' = \frac{Rt'}{Rt}(234.5 + t) - 234.5$.
and, $t' - t_a$ = the temperature rise at the time of measuring $Rt'$.

### OVERLOAD TEMPERATURE TEST

If an overload run is specified, for example, 150 percent load for two hours, to immediately follow the normal load run, the duration of which is such that the transformer will not reach a constant temperature, it is obvious that the overload run should be started at the normal load temperature, hence, if the temperature of the transformer has fallen appreciably during the time taken to measure the hot resistance and to reconnect, the normal load run must be resumed and continued until the normal load temperature rise has been reached (temperature rise of oil). The specified overload should then be applied immediately and readings taken every half or quarter hour, as may be required.




## How to Repair Old Squirrel-Cage Rotors

TWO general types of windings were used in the early squirrel-cage induction motor rotors. One, the bolted-on end ring type, had the bars bolted to the end rings with iron screws and lock washers. The other, the keystone type, had the end rings made in sections. These were slipped over the ends of the rotor bars and were riveted and sometimes soldered to the bars.

Many of both of these types of rotors are still in service and some of them occasionally require repairs. The principal difficulty is either that the motor overheats or that it does not come up to speed.

High rotor resistance, due to oxidation between the bars and end rings, causes the rotor to heat and not to come up to speed. The oxidation is due to expansion and contraction of the rings and bars as they heat and cool when the motor is operated under changing load conditions. The lock washers lose their temper when the motor gets extremely hot from overload, and do not maintain proper pressure between ring and bars.

On the keystone type rotor, the troubles are practically the same and are also due to oxidation or poor contact between the bars and the sectional end rings.

In many shops it is customary to make repairs to the rotor by removing the bars and end rings, grinding off the burned spots and replacing the bars, using new screws and lock washers. There is another method which requires less time for repairing a rotor and makes practically a permanent job without dismantling the rotor.

All grease and dirt is cleaned from the bars and end rings, particularly at the point of contact; and on the underside of the ring a gas flame mixed with air pressure is applied until a bright red heat is reached. Oxy-acetylene is then applied, together with a 3/16 inch stick of "Tobin" bronze dipped in brazing flux, and the bar is securely brazed to the ring. Care should be taken not to deposit any more brazing flux than is absolutely necessary to make a good contact between the bar and ring.

This method should not be used with end rings having a small percentage of copper or a low melting point metal, such as rotors with high resistance end rings and rotors used for elevator service. For rotors of this class, a more satisfactory job can be made by using silver solder with borax as a flux, and applying only enough heat to cause the silver solder to run freely around and between the bar and ring.

The heat used in warming up the rotor, as a rule, destroys the insulation on the rotor bars. In place of reinsulating the bars with fish paper, a suitable cement is used. This cement is forced into the rotor slot between the rotor bars and iron with a putty knife until there is practically no play between

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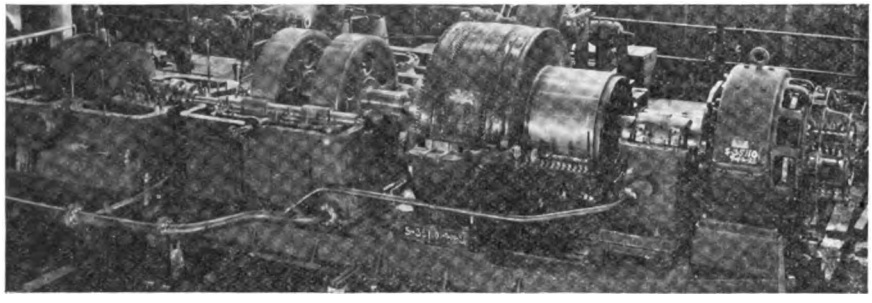
the rotor bar and the slot. This is best done while the rotor is hot, as the cement will dry much more quickly.

As a rule after the repairs are completed, it will be found that the starting torque of the motor has been decreased due to a better contact between the rings and the bars or on account of too much metal being deposited at the point of the weld. To remedy this, the rotor can be placed in a lathe and a cut made on the outside end of each ring. The amount of cut made depends entirely upon the change in speed before and after brazing, and can best be determined by experience.

## Motor Drive for the World's Largest Ferries

THIS direct-current turbine-generator illustrated supplies motive power for the world's largest and most modern motor-driven ferry boat. The *Peralta* and its sister ship, the *Yerba Buena,* which is powered by a similar unit, carry commuters between San Francisco and East Bay Cities and connect with the electric trains at Oakland. Each main power unit, as shown, consists of a steam turbine driving a 1900 kw direct-current generator through one unit of two herringbone reduction gears, and a direct-coupled exciter. Each ferry has two propellers, one at each end. Individual 2250 hp motors are used to drive the propellers. When the ferry is crossing the bay in one direction the propeller at the forward end is rotated slowly by its motor so as not to be a drag on the boat. When the direction is reversed what was the bow becomes the stern. The idling propeller for one direction becomes the driving propeller on the return. About fifteen percent of full-load power is required to run the idling propeller. Because of its great superiority for speed control, so essential in ferry boat maneuvering, direct current is used to give variable voltage control, full control of both motors being maintained in the pilot house.



## Transformer Taps Come from the Middle and Not the End of the Winding

THE end turns of a transformer are the ones most likely to be punctured by a voltage surge. These end turns, then, are provided with extra insulation, which is called padding. Variable voltage taps could be taken off at the ends of the windings. This would mean cutting through the padding, thereby materially lessening its effectiveness. Furthermore, the taps themselves would require padding; also the terminal board or tap changing switch would need insulation capable of withstanding voltage surges. By bringing out the taps from the interior of the winding, these insulation difficulties are mitigated. Furthermore, a better space factor is secured and the total cost reduced. Altogether, there is much less chance of a fault occurring and less danger of its being serious if it should occur.

There is one exception to this rule and that is in the case of transformers made for grounded star connection. In these transformers, taps are taken from the grounded side of the winding to minimize the voltage to ground, as before, and because this is the point of least surge stress.

## Stripping Impregnated Motor Windings

A. C. ROE

IN removing the coils from an armature preparatory to rewinding, the problem is to get the coils out of the slots with the least amount of time and effort, to leave the slots as clean as possible, and to do the minimum of damage to the laminations and other good motor parts. The methods described here have been used in one large repair shop and found satisfactory.

If the winding is in such condition as to allow current to be circulated through it, that is, it is not open circuited or fused to ground, allow approximately three to five times full-load current to flow through the winding. The end bells of the motor should be first removed to allow free movement of air. The current should be left on until the winding is completely roasted out. As a precaution, the line should be fused for about 10 percent more current than is used, so that when the winding becomes short-circuited due to destruction of the insulation, the line will be protected. After the winding is completely roasted out, the ends of the coils on one side of the should be cut off flush with the laminations by means of a cold chisel having a wide, flat blade. The coils can then be pulled out with a wrecking bar and a block of wood while the motor is still hot.

If the winding is open-circuited, or fused to ground, a gas or brazing torch can be used effectively. An adjustable stand for holding the torch will be useful and will save time in stripping wound-rotors or shoved-through type windings. The coils should be cut as before and the windings pulled out while the flame is being directed on the coils. With this method of heating, the old cell insulation is easily removed.

Another method of removing the coils after they have been cut is to use a long tapering steel wedge fitted in an air hammer. One end of the wedge is shapped to fit in the air hammer and the other is inserted under the coil at the end of the slot nearest the commutator and the air is turned on the hammer. The tool is then moved into the slot forcing out the coil.

If this last method of removing the coils is used the slots should be freed from all old insulation by directing the flame of a blow torch into them.

After the stator is stripped, if there is any grease or oil on the frame, the stator should be sprayed with gasoline and wiped clean. The laminations should be examined and if any sharp points in the slots are found they should be filed off. Boiling the end bells and other parts in "Oakite" or "Wyandotte" cleaner removes all dirt and grease.

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# A Method for Testing Transformers and Meters at Reduced Power-Factors, Using Non-Reactive Loads

C. G. VEINOTT

THERE is a fairly simple method for making regulation tests on single-phase transformers at power-factors between 50 percent leading and 50 percent lagging whereby the customary reactors, condensers, or synchronous machinery are unnecessary for loads. A three-phase supply system and non-reactive load can be made to accomplish this purpose. By an extension of the same method, phantom power-factors ranging from zero percent leading to zero percent lagging, suitable for the calibration of wattmeters, watthour meters, or power-factor meters, can be obtained.

## TRANSFORMER TESTING

The variation of secondary terminal voltage of a transformer with load, primary voltage being constant, can be calculated for any power-factor from the open-circuit secondary voltage, equivalent resistance and equivalent leakage reactance. Manufacturers who have a large number of transformers to test usually obtain the leakage impedance from a short-circuit test and calculate the regulation. School laboratories frequently like to determine a regulation curve by actually loading the transformer. Operating men, sometimes

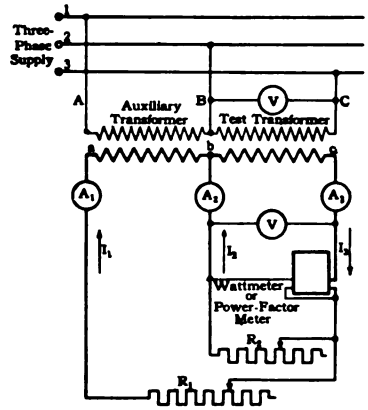


FIG. 1—CONNECTIONS FOR LOADING A TRANSFORMER AT VARIOUS POWER-FACTORS

wish to make similar tests as there is a great deal of satisfaction in obtaining performance curves by actual test rather than by calculation.

Usually, there will be little difficulty in determining a regulation curve at unity power-factor because non-reactive loads such as lamp banks, water rheostats, or grid resistors are easily available. It is in providing power-factor loads that difficulty arises in the less elaborately equipped plants, for, unless suitable synchronous machines are available, reactors and condensers are generally used. At best, reactors are not very satisfactory and not infrequently it is difficult, if not impossible, to obtain enough condenser capacity to load the transformer to the desired value. Even when this is impossible it is usually difficult to hold the power-factor constant when varying the current. Synchronous machines, are not entirely satisfactory as loads, due to low stability at low power-factors and hunting tendencies.

A scheme is shown in Fig. 1 where, by using adjustable resistances of any kind for a load, the power-factor of the transformer on test can be made practically anything from 50 percent leading to 50 percent lagging. The primary of the transformer on test is connected in V with the primary of another transformer of the same turns ratio. The secondaries are also connected in V. If any doubt exist as to the polarities of the transformers, this may be checked with a voltmeter. If the voltage between outside secondary lines is the same as that across either transformer secondary, the connection is correct. One adjustable resistance is connected across the secondary of the transformer to be tested, and another across the outside terminals of the V. Ammeters are inserted to measure the current in either resistor and the current in the secondary of the transformer under test. Voltmeters are connected to measure primary and secondary voltages of the test transformer. A wattmeter, or power-factor meter, is also connected to the secondary side.

TABLE I—POWER FACTORS FOR VARIOUS CURRENT RATIOS.

| 100 to 50 Percent Power-Factor Range | | | | 50 to 0 Percent Power-Factor Range | |
|---|---|---|---|---|---|
| $I_1/I_2$* | cos θ | $I_2/I_1$* | cos θ | $I_1/I_2$* | cos (60 − θ) |
| 0.0 | 1.0000 | 1.0 | 0.8660 | 0.0 | 0.5000 |
| 0.1 | 0.9966 | 0.9 | 0.8505 | 0.1 | 0.4271 |
| 0.2 | 0.9878 | 0.8 | 0.8323 | 0.2 | 0.3592 |
| 0.3 | 0.9754 | 0.7 | 0.8109 | 0.3 | 0.2968 |
| 0.4 | 0.9608 | 0.6 | 0.7857 | 0.4 | 0.2402 |
| 0.5 | 0.9449 | 0.5 | 0.7559 | 0.5 | 0.1891 |
| 0.6 | 0.9286 | 0.4 | 0.7206 | 0.6 | 0.1429 |
| 0.7 | 0.9122 | 0.3 | 0.6786 | 0.7 | 0.1014 |
| 0.8 | 0.8962 | 0.2 | 0.6286 | 0.8 | 0.0640 |
| 0.9 | 0.8808 | 0.1 | 0.5695 | 0.9 | 0.0303 |
| 1.0 | 0.8660 | 0.0 | 0.5000 | 1.0 | 0.0000 |

* $I_1$ = 60 deg. component, $I_2$ = in phase component.

The power-factor of the transformer is controlled by the ratio of the two resistances $R_1$ and $R_2$, and the load current by the absolute magnitude of these resistances. The vector diagram, Fig. 2 shows why this is so. $E_{bc}$, the voltage of the test transformer, either lags or leads $E_{ab}$, the voltage of the auxiliary transformer, by 120 deg. Assume, for the present, that $E_{bc}$ is leading. The secondary current $I_3$, as measured by the ammeter $A_3$, is the vectorial sum of the two currents taken by the two resistances, $R_1$ and $R_2$. The current taken by the resistance $R_1$ is in phase with the voltage that drives it, namely, $E_{ac}$. Since the windings are in series, $E_{ab}$ added to $E_{bc}$ gives $E_{ac}$, numerically equal to $E_{bc}$ but 60 deg. behind it as shown. Therefore, since $I_1$ is in phase with $E_{ac}$, it lags the voltage of the test transformer by 60 deg. $R_2$ is directly across the secondary of the test transformer, therefore the current $I_2$, taken by it, will be in phase with $E_{bc}$. The load current delivered by the test transformer is the vectorial sum of $I_1$ and $I_2$, or $I_3$ as shown.

It will be observed that the load current of the transformer lags behind the transformer voltage, even though only non-reactive loads are used. It will further be observed that

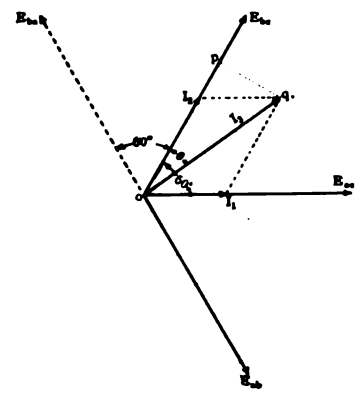


FIG. 2—VECTOR DIAGRAM SHOWING HOW VARIOUS POWER-FACTORS MAY BE OBTAINED

any angle of lag between 0 and 60 deg. may be obtained by varying the ratio of $I_1$ to $I_2$.

This arrangement for obtaining reduced power-factors can also be used with a two-phase, three-wire system. The apparatus should be hooked up as shown in Fig. 1, care being observed to connect the common point of the primaries of the two transformers, $B$, to the neutral wire. In this case, the maximum angle of lead or lag will be 45 degs. It should

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be remembered when selecting resistors that the voltage across $R_1$ will be 41 percent higher than that across $R_2$.

The power-factor obtained with any given ratio of currents can be easily calculated. It is evident in Fig. 2 that

$$\tan\theta = \frac{pq}{op} = \frac{0.866\, I_1}{I_2 + 0.5\, I_1}$$

or, using current ratios instead of actual currents, this becomes

$$\tan\theta = \frac{0.866}{I_2/I_1 + 0.5} \text{ or } \frac{0.866\ (I_1/I_2)}{1 + 0.5\ (I_1/I_2)} \quad \ldots\ldots\ldots (1)$$

Knowing tan $\theta$ from this expression, cos $\theta$, or the power-factor can be found in trigonometric tables. A number of power-factors have been so computed and the results plotted as the upper curve of Fig. 3. On the left half of the figure the abscissae are the ratios of the 60 deg. component to the in-phase component, that is, $I_1/I_2$. On the right half of the figure the abscissae are the ratios of $I_2$ to $I_1$. In this way the entire range of the ratios of currents can be plotted. The ordinates are the corresponding power-factors of the transformer on test.

In the above discussion, only lagging power-factors have been considered. It is equally easy to obtain leading power-factors. Referring again to Fig. 2, it will be seen that the same component of current which lags the voltage of the test transformer by 60 deg., i.e. $I_1$, leads the voltage of the auxiliary transformer by 60 deg. If a third resistance is connected across the terminals of the auxiliary transformer, any desired power-factor from 100 to 50 percent leading, may be obtained on the auxiliary transformer. However, we are not interested in the power-factor of the auxiliary transformer but we can interchange the test transformer and its shunted resistance with the auxiliary transformer. Thus, connected in this manner, any leading power-factor between 50 and 100 percent can be obtained in the test transformer. This is exactly what will occur if $E_{bc}$ lags $E_{ab}$ instead of leading it, as first assumed. The interchange of auxiliary and test transformers can be effected on the primary side in a simple way by changing lead $A$ to line 3, and lead $C$ to line 1.

In the above discussion and in figuring the curve of Fig. 3 it has been assumed that the voltages of the two transformers are exactly equal and 120 degrees apart. This is not

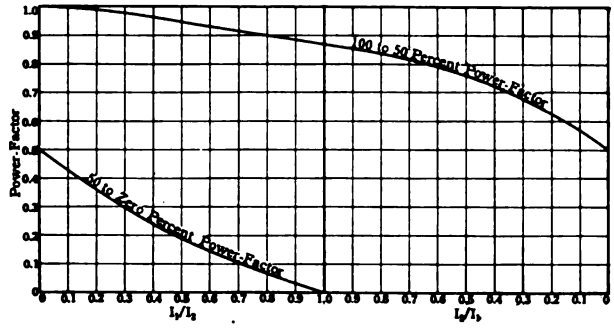


FIG. 3—DETERMINATION OF POWER-FACTOR FROM CURRENT RATIOS

quite true when the transformers are loaded due to their impedance, since the terminal voltages shift in both magnitude and phase position. This effect is illustrated by the vector diagram of Fig. 4 which represents the conditions when $R_2$ is open-circuited. In this diagram the $IR$ and $IX$ drops have been greatly exaggerated. $I$ is the current common to both transformers; $V_1$ and $V_2$ are open-circuit voltages, equal and 120 degrees apart; $E_1$ and $E_2$ are terminal voltages. However, this affects only the limiting power-factors obtainable. With transformers of 1.4 percent resistance and 4.0 percent reactance, the minimum power-factors obtainable are 43 3 percent lagging and 54.0 percent leading, if the primary voltages are constant. Of course the primary voltages may change if a limited source of power is used.

*Method of Test*—The test procedure may be summarized briefly as follows;—connect the transformers to be tested with another suitable transformer of the same voltage ratio as shown in Fig. 1. Measure the voltage across the outside terminals of the secondaries, that is, the voltage from *a* to *c*. If this is the same as the secondary voltage of either transformer the connections are correct; if it is about 73 percent larger, disconnect the secondary lead of the test transformer from the auxiliary transformer and connect the other secondary lead of the test transformer to the same secondary

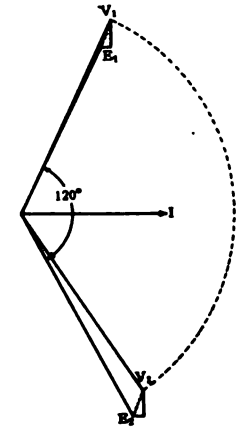


FIG. 4—THE EFFECT OF IMPEDANCE ON TRANSFORMER VOLTAGE

lead of the auxiliary transformer just used. Leaving $R_2$ and $R_1$ open, measure the voltage of the test transformer. Holding the primary voltage of the test transformer constant, connect $R_1$ and decrease its resistance gradually, at the same time observing the secondary voltage of the test transformer. If the secondary voltage falls as load is applied, the connections are such that the power-factor in the test transformer is lagging; if the secondary voltage remains constant or rises as load is applied, the power-factor is leading. If the power-factor is lagging, and a leading power-factor is desired, interchange the leads on the primary side, i. e. in Fig. 1 change $A$ to line 3 and $C$ to line 1. Control the power-factor by varying the ratio of $I_1$ to $I_2$ and the load current by varying both resistances in the same ratio. For 80 percent power-factor, $I_1$ will be about 50 percent larger than $I_2$. Other approximate ratios of $I_1/I_2$ for any power-factor can be taken from Fig. 3 using only the upper curve.

## METER TESTING

For testing meters at various power-factors a phantom power-factor is sufficient as it is not necessary that the cur-

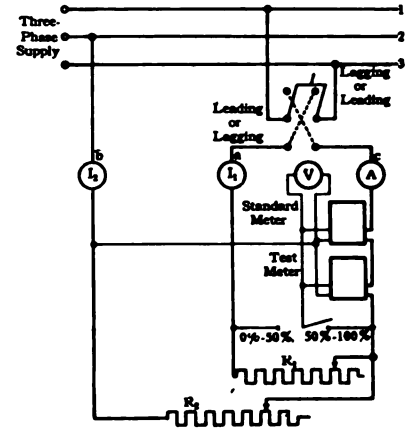


FIG. 5—A SCHEME FOR OBTAINING ANY PHANTOM LOADING OF METERS AT ANY POWER-FACTOR

rent in the current coil of the instrument be supplied by the voltage impressed across the terminals of the voltage coil. This makes it possible to obtain any power-factor for testing instruments, using an arrangement essentially as outlined above. This method may be used for testing wattmeters or

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watthour meters at a low power-factor or may be used for calibrating a single-phase power-factor meter.

Referring again to Fig. 2, it will be observed that $I_3$ lags the voltage $E_{ba}$ by $(60 + \theta)$ degrees. If $\theta = 30$ degs. $I_3$ will be 90 degs. behind $E_{ba}$. Thus zero percent power-factor can be obtained on a wattmeter by connecting the potential coil to read the voltage $E_{ba}$, and passing $I_3$ through the current coil. When meters are being tested, the transformers of Fig. 1 are unnecessary if the three-phase source is of the proper voltage.

A scheme for connecting the meters is shown in Fig. 5. The current coils of the meters to be tested, including that be a standard meter, are connected in line *c*. The potential coils of the instruments are connected in parallel. One side of the parallel connection is permanently joined to line *b*, the other side can be connected to either line *a* or *c* by means of the double-throw, single-pole switch. When thrown to the left, the range of power-factors obtainable is from 0 to 50 percent; when it is thrown to the right, the range is from 50 to 100 percent. The position of the double-pole, double-throw switch determines whether the power-factor is leading or lagging. It is desirable to have the single-pole switch thrown to the right when determining which position of the double-pole switch gives a lagging power-factor or when checking the polarity of each potential coil with respect to its current coil. If this is not done, the current in the current coils may be more than 90 degs. behind the voltage across the potential coils.

The power-factor is controlled by the ratio of the currents $I_1$ and $I_2$. The power-factor in the instrument is cos $\theta$ for the 50 to 100 percent range (single-pole switch in right position) and cos $(60 + \theta)$ for the zero to 50 percent range (single-pole switch in left position.) The power-factor in the instruments is plotted in Fig. 3 as a function of the ratios of these two currents. The upper curve is to be used when the power-factor range is from 50 to 100 percent and the lower curve when the range is from 0 to 50 percent. The current ratio may be used as a rough indication of the power-factor, the accuracy of this indication being dependant upon the degree of balance of the three phase supply and its freedom from large harmonies, and the absence of reactance in the resistors.

While this method of obtaining reduced power-factors is not as convenient as using a phase shifter, it can be used where a phase shifter is not available. In fact, this method has been used more or less extensively, even for routine testing.

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# The JOURNAL QUESTION BOX

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2865—APPLICATION OF DISTRIBUTION FACTOR—Professor Alex. Gray on p. 187 of "Electrical Machine Design" discusses the distribution factor. The following is taken from his discussion:—In Fig. (a) conductors *A* and *B* are connected in series, therefore the vector sum is $2e \times 0.96 =$ resultant voltage, *e* being voltage per conductor. He uses two conductors. In Fig. (b), he uses three conductors or $3e \times 0.91 =$ resultant. In Fig. (c) he uses (where all conductors are used) $6e \times 0.64$. In Fig. (d) he uses (if only four or six slots per pole are used) $4e \times 0.84 =$ resultant. Now in three phase he uses two coil sides. In two phase he uses three coil sides. In one phase he uses all coil sides. Why is it that in a two and three phase he uses one-half of the total coil side while in single phase he uses all coil sides? Now in Fig. (c) each coil side is drawn as one line each 30 degrees out of phase with the adjacent slot. Therefore in the case of single phase he gets the voltage of all coils, while in case of two, three phase he gets the voltage of one-half the total voltage. This is because he is using only half of the conductors. I think that he is right in case of Figs. (a) and (b) to use half the total coil sides. Then why isn't it right to use half the coil sides in case of single-phase diagrams (c) and (d)? C. L. R. (MASS.)

In discussing the distribution factor, Professor Gray used six slots per pole. This number gives a value of slots per pole per phase of two for three phase; three for two phase, and six for single phase. The value he obtains for the three-phase condition is for leg voltage. For the same value of volts between conductors a star connection gives a

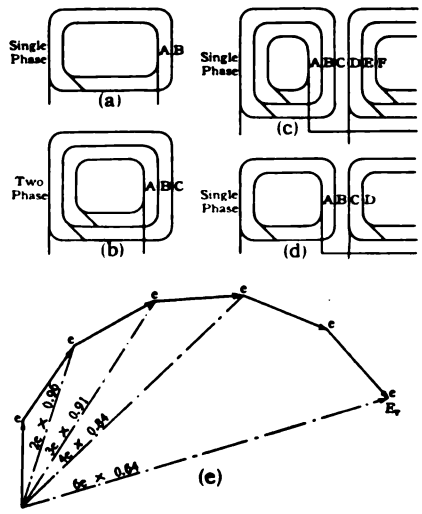


FIG. 2865

higher value of terminal voltage than a delta connection. Consequently, nearly all machines are star connected. The value of terminal voltage for three-phase star, is $1.732 \times 2e \times 0.96$ and for three-phase delta is $2e \times 0.96$. In regard to the latter part of the question: He uses one third of the slots for three phase, one-half for two phase and the full number for single-phase. It is obvious that this is correct as he must have three-phase belts in the first case, two-phase belts in the second case, and a one-phase belt in the third case. M. U. M.

2866—METER RELATIONS—A wattmeter connected correctly would give a vector diagram as in Fig. (b). But with common lead broken at *X* Fig. (a) would the vector diagram be as in Fig. (c)? 1—If it is not correct, please give the correct one. 2—If it is correct would you show me the error in my reasoning. Referring to Fig. (c) it seems to me that the upper element would tend to rotate the disk backwards with half torque. Because the potential vector (1-3) seems to lead $c_3$ 30 degrees same as if potential (2-3) had swung back 120 degrees and the potential per coil is obviously one-half normal. And for the lower element the potential seems to have swung 120 degrees ahead, and backward rotation should be the result. But from test it goes ahead about half normal speed. E. L. (N. Y.)

The sketches are all right but the trouble is in the line of reasoning. Voltage 2-3 is not 120 degrees from 1-3, but is only 60 degrees, in other words 2-3 is 120 degrees from 3-1, and 60 degrees from 1-3. Also 1-2 is 60 degrees from 1-3 and 120 degrees from 3-1. When the wire is cut at *X* the following conditions exist in the meter

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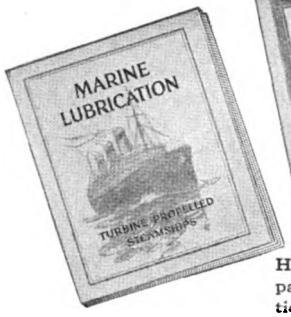


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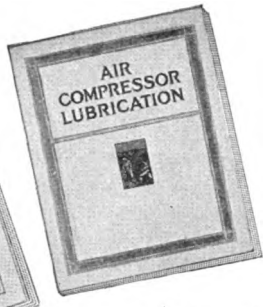


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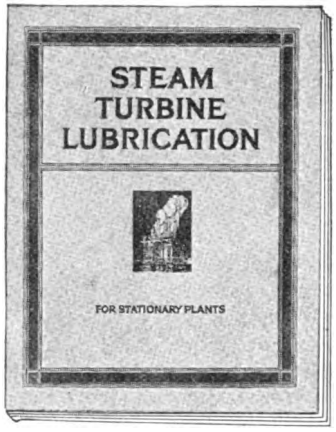


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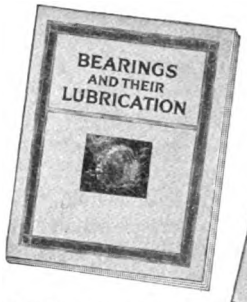


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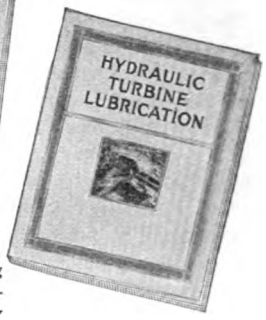


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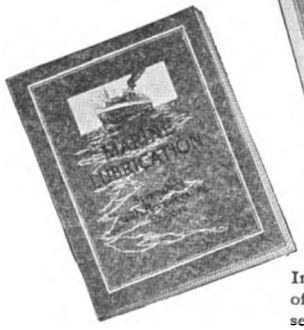


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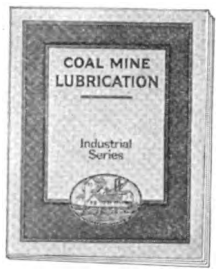


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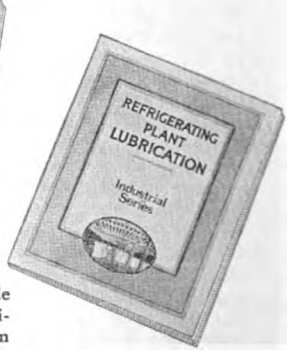


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at unity power-factor, balanced loads. In the upper element the voltage impressed on the shunt coil is $\frac{1}{2}$ $E_{1\text{-}3}$. The current in the current coil is $I_{0\text{-}2}$ and lags the voltage 30 degrees. This element then measures,—

$\frac{1}{2}$ $E_{1\text{-}3}$ $I_{0\text{-}3}$ cost 30 deg. = $\frac{1}{2}$ $EI$ cos 30 deg.

In the lower element the voltage impressed on the shunt is $\frac{1}{2}$ $E_{3\text{-}1}$, and the current in the current coil is $I_{0\text{-}1}$. The current leads the voltage 30 degrees. This element then measures,—

$\frac{1}{2}$ $E_{3\text{-}1}$ $I_{0\text{-}1}$ cos 30 = $\frac{1}{2}$ $EI$ cos 30 deg.

The total measured by the meter is the sum of that measured by both elements and is,—

$EI$ cos 30 degrees = 0.866 $EI$

As the true power at unity power-factor balanced load is 1.73 $EI$, the meter is measuring only half the load. If the power-factor is not unity the currents are displaced from their unity

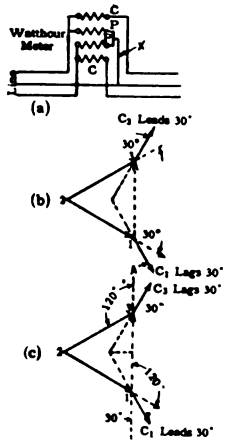


FIG. 2866

power-factor positions by an angle $\phi$. The upper element measures,—

$\frac{1}{2}$ $E_{1\text{-}3}$ $I_{0\text{-}3}$ cos ($\phi$ + 30)
= $\frac{1}{2}$ $EI$ cos ($\phi$ + 30)

The lower element measures,—

$\frac{1}{2}$ $E_{3\text{-}1}$ $I_{0\text{-}1}$ cos ($\phi$ − 30)
= $\frac{1}{2}$ $EI$ cos ($\phi$ + 30)

Combining that measured by the upper and lower elements gives,—

0.866 $EI$ cos $\phi$

which is only one-half the true power; the true power being $\sqrt{3}$ $EI$ cos $\phi$.

C. O.

2867—Unbalanced Load From Autotransformers—It is desired to supply 110 volt, three-phase service to an unbalanced load from a 220 volt supply. To this end 2300-220-110 volt transformers would be used and connected as shown in Fig. (a) and (b), the primary being left open; single-phase loads $a$, $b$, $c$,; transformer impedance $Z_1$, $Z_2$, $Z_3$; load impedance $z_1$, $z_2$, $z_3$. I would appreciate a solution of a problem of this kind, showing the divisions of the load in different transformer windings in order to select the proper transformers for such an arrangement. A. G. (Ind.)

This question requires a general solution for a three-phase circuit, consisting of a delta-connected load, fed by two autotransformers connected in open delta. The only way that the autotransformer, would have any effect on the distribution of the current in the load would be through their regulation. By this regulation the voltages delivered by the auto are slightly unbalanced, both as regards magnitude and phase position. Since the impedance of autotransformers is usually very low, this unbalance will be quite small and, therefore, its effect on the current distribution in the load will be small. A general solution of the problem taking into ac-

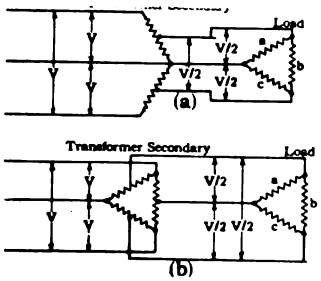


FIG. 2867

count the regulation of the autotransformer would be quite complicated and not worth while for ordinary use. An analysis of the open delta connection will be found in the Journal, Vol. XIII, 1916, p. 100. The division of load in a delta connected load is also discussed in the Journal, Vol. XIV, 1917, p. 350; and Vol. XXII, 1925, p. 121.

E. G. R.

2868—Transmission Problems—I am to construct a power line 21 miles long, for a 40 kw maximum load. This load is to be carried by a three-phase, 2400 volt generator. On account of local and mechanical conditions, wire must be aluminum cable No. 6 or higher. On account of the high price of wire and line materials here and as a small size wire cannot be used and also due to local conditions the construction of a two wire line costs about half of a three wire of the same size. What is the most practical manner to transform (static) the three-phase to single-phase so as not to unbalance badly the 75 kv-a generator which must also furnish three-phase current locally? What is the best line voltage? Bus-bar voltage 2300. Kind of transformers, approximate prices and how many? Load is about 20 kw at night for lighting only; and day load is 30 kw motors and 15 kw for coffee machinery. Power loss if necessary can be high, but voltage regulation must be about 5 percent which is the local regulation. Generator is regulated by an automatic voltage regulator. The approximate cost of the construction of a three-phase line with No. 6 aluminum cable was calculated at $10 000, a two line of same wire due to local conditions is much better in all respects, and possibly half as cheap. R. G. (South America)

The problem of transmitting 40 kw by single phase a distance of 21 miles with a five percent voltage regulation and using No. 6 aluminum cable, could easily be accomplished if it were not for limitations in the generator. A three-phase, 75 kv-a generator will have only 57 percent of its rating when run as a single-phase machine or approximately 43 kv-a. Certain types of three-phase machines are not suitable for single-phase operation at all without the addition of damper windings to take care of the pulsating flux caused by the single-phase operation. Your letter did not give us sufficient information to determine what type of machine you have, whether a small turbogenerator or an engine type. However, we believe that its ratings is not sufficiently high to carry a 40 kw single-phase load in addition to the local three-phase load, besides having the disadvantage of having an unbalanced voltage at the local three-phase load. With these limitations in mind we have worked up the problem of transmitting 40 kw over the 21 mile distance for a voltage regulation of five percent. Using a No. 6 aluminum cable, and three-phase transmission with an equivalent delta spacing of 24 in., we found that in order to meet the five percent voltage regulation conditions it would be necessary to use an 11 000 volt line. With this voltage the transmission losses will be very low. At the sending end the transformers necessary will be three 15 kv-a transformers with voltage of 2300 to 11 000. At the receiving end the number of transformers necessary will probably depend upon the location and kind of load. The increased cost of the three-phase transmission line is somewhat balanced off by the flexibility at the receiver end, in that three-phase motors can be used, and the unbalanced single-phase load can be distributed among the three phases, and the motors running will tend to balance up the three-phase voltage. It has been our experience that the additional cost of the three-conductor line over the two conductor line is little greater than the additional cost of the extra conductor and insulator. B. V. H.

2869—Television Broadcast—I wish to know the wave length or (frequency) at which K.D.K.A. broadcasts television, also the schedule of the transmissions. I understand that the plate voltage for television receiving sets cannot be supplied by "B" eliminators because of the impracticability of adequate filtering. Will an ordinary 220 volt direct-current motor operated as a generator provide a suitable current supply for television sets if provided with a reasonable filter?

H. B. F. (Pa.)

K.D.K.A. transmits television signals frequently on 63 meters. However, other wave lengths are also occasionally used. It must be remembered that this is experimental work and therefore no schedules are regularly maintained. Rectified alternating current or "B" eliminators can be used for receiving sets if proper filter circuit is used. The 220 volt direct-current motor can be used as a generator for this purpose provided the commutator is such as to provide a fairly smooth direct current. In any case a filter will be required. You are doubtless aware of the fact that television signals cannot be picked up and translated into a picture unless the film drum on the receiving apparatus is synchronized with the scanning wheel on the transmitting apparatus. The number of apertures in the scanning wheel used is sometimes 48 and sometimes 60. C. W. H. and A. M. D.

2870—Hunting—We have a 650 kv-a generator which is giving considerable trouble due to hunting. This generator is direct connected to a horizontal reaction water wheel. As shown by Fig. (a) generating station $C$ is tied to the main system through a loop 6000 volt line from substations $A$ and $B$ and 43 miles of 44 kv line. The generator will operate quite satisfactorily if the exciter voltage is maintained between 40 and 50 volts. However, if the generator field rheostat is turned in and the exciter volt-

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age raised correspondingly, the alternating-current ammeters start oscillating and as the effect is cumulative. The automatic oil switch opens ten or fifteen seconds from the time the first hunting is noticed. In raising the exciter voltage no change was made in the excitation current supplied to the generator. For this reason we thought the difficulty could be overcome by adding a resistance in parallel with the generator field. However, such a resistance does not improve operating conditions. There are times when the exciter voltage may be varied at will and perfect operation obtained with the same load and line conditions in so far as we are able to determine. The induction voltage regulators used on the distribution lines feed from this loop will not operate satisfactorily when this generator is synchronized with the system. Have you any suggestions for correcting this condition? Do you believe a damper winding will eliminate the trouble? How large copper would you use in such a damper winding? G. R. O. (UTAH)

The variations of the alternating current are probably caused by a defective generator field rheostat. The indications are that a bad contact exists in the part of the rheostat which is not in the circuit when the exciter is operating between 40 and 50 volts. As the exciter voltage is increased and the generator field rheostat is turned in, the defective part of the rheostat is connected in the field circuit. The variable contact causes the field current to be varied through a wide range. Each change in excitation causes a change in the load, which causes a momentary change in speed. The effect of varying field current upon the slight changes in speed would be cumulative and would result in the generator falling out of step and opening of the automatic oil switch. There are probably times when the temperature is such that the contact does not vary and operation is satisfactory. Since a waterwheel is a constant torque prime mover, there is no necessity for damper windings in the generator unless provision is made for automatic synchronizing or for operation of the generator as a self-starting synchronous condenser. You do not give sufficient information regarding the induction voltage regulator to enable us to express an opinion as to the probable cause of the trouble.

C. C. H.

2871—THREE-WIRE DIRECT-CURRENT GENERATOR WITH ONE NEUTRAL RING—Please describe the current in a three-wire, 110-220 volt, direct-current generator neutral, where only one neutral ring is used. The generator is 8 pole and the neutral has four taps to the armature, spaced every other pole. Equalizers are used on the armature. What effect on commutation will a large unbalanced or neutral current have. Would this 110 volt or neutral current be satisfactory for use as synchronous motor exciting current? No inductive reactances are connected in the neutral.

J. A. W. (OHIO)

It has been assumed that the machine referred to is of the rotating balance coil type which is the construction usually employed when only one ring is used. The fact that the question states that four taps are taken from the armature spaced every other pole, makes the question a little ambiguous as it would be impossible to obtain three-wire operation under these conditions. When one-ring neutral is used, taps are taken from the armature at points 180 electrical degrees apart. These taps are then taken directly to the ends of a balance coil which rotates with the armature instead of bringing the taps out to slip rings as is the case in the two-ring neutral. The midpoint of the balance coil is then taken to a slip ring which becomes the neutral for the machine. The four taps referred to as coming from the armature are probably four taps taken from the midpoints of four of these balance coils. As far as operation is concerned, it is exactly the same in the case of the one-ring neutral as in the case of the two-ring neutral, and the 110 volt circuit could be used for synchronous motor exciting current or any other use to which a 110 volt circuit might ordinarily be put. Three-wire machines are usually built for an unbalance up to 25 percent. Up to this point, the unbalance will have very little effect on commutation. If the unbalance is greater than this, sparking may occur due to the fact that the interpoles are not uniformly excited. The interpoles are connected in two circuits, the poles of one polarity being connected at one side of the armature and the poles of the other polarity at the opposite side.

A. M. H.

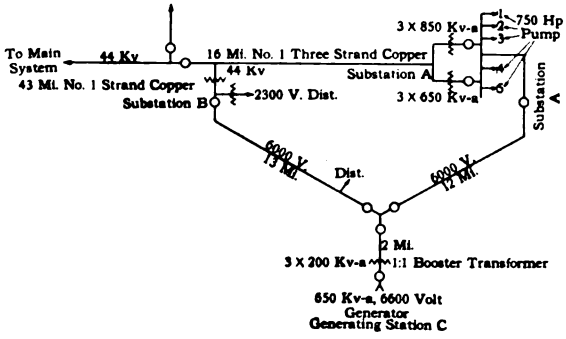


FIG. 2870

2872—A 60 CYCLE WOUND ROTOR MOTOR ON 50 CYCLES—Will you furnish me with data regarding the performance of a 500 hp, three-phase, 2300 volt, 60 cycle slip ring motor when connected to a 50 cycle source of the same voltage? What will be the primary and secondary amperage for out-put of the motor on 50 cycle current from 250 to 450 hp; what will be the effect on power-factor and efficiency? If output is allowed to drop to a maximum of 450 hp will there be objectionable heating during runs not to exceed two hours? Will the present control resistance whereby a 30 percent reduction in speed is obtained give approximately the same results when operating with the new frequency? R. F. S. (COLO.)

A 60 cycle motor operating from a 50 cycle source at rated voltage will have considerably increased flux in the iron core, which will mean increased magnetizing current and probably increased iron losses to the point of almost dangerous heating. This will depend on how liberally the motor was designed in the first place and without having specific data as to the design constants of your particular motor we cannot make a definite statement. In general, however, a motor of reasonably modern design will probably get abnormally warm, even at no load, due to the excessive iron losses under these conditions. The motor will also run at approximately five-sixths its normal speed which will mean less ventilation and hence still further increase in temperature. The power-factor and efficiency will both be decreased. At the same voltage, the working component of the current for the same load should be the same regardless of frequency. As stated above the magnetizing current will be increased. This will doubtless result in some increase in total current and hence increased copper losses. This effect, however, can be overcome by decreasing the rating of the motor, as should be done, in proportion to the decreased speed. To obtain satisfactory operation, a 60 cycle motor connected to a 50 cycle source of supply should have the impressed voltage decreased in direct proportion to the frequency. If the motor referred to in your question could be operated on 2000 volts at 50 cycles you would get very close to normal performance in all respects except that the motor rating and the motor speed would be decreased in proportion to the decrease in frequency. There is one saving feature in your problem. It requires considerable time for a motor as big as 500 hp to reach its maximum temperature and if the load is decreased to 450 hp, it is entirely possible, even probable, that the motor would not reach a dangerous temperature within two hours. Because of the somewhat increased current, the present control resistance would give a somewhat greater percentage speed reduction at the same load and would also get somewhat hotter but probably not enough to make any great difference. You must understand that all of the above are merely general statements. Individual motors of the same general line vary considerably in their characteristics, and motors of different manufacturers are apt to vary considerably so that no one but the manufacturer of the particular motor can tell you exactly what it will do under the given circumstances. My suggestion would be that you try the motor under the suggested circumstances and see how long it takes it to get undesirably hot. C. R. R.

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# THE ELECTRIC JOURNAL

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**The Public Utility Engineer**

If an engineer is to succeed in the public utility industry under present conditions, he must make himself a scientific business man. In this phrase, "scientific" may be said to refer to the laws and forces of nature and their application to the use of man, while "business man", as usual, means one who performs a useful service to his fellow men in such a manner as to earn a profit for his employer and himself. In other words, scientific refers to the engineer's dealings with the laws of nature, while business man assumes dealings with his fellow men.

Business knowledge and judgment come from a broad gauge understanding of the business in which the engineer is engaged. Almost every engineering graduate, having at his command the data and records of past experience now available, can make an acceptable engineering design, but trained judgment not gained from purely technical work is required to determine when and where system additions should be built, what capacity they should have, and how much money may be spent on them, based upon the earning power.

AMONG the factors, concerning which the public utility engineer must develop good judgment, are the habits and customs of the people whom his company serves, for the development of a utility system is based on the loads it is expected to carry and these in turn are based on the habits of the people served. Predictions of future load, both as to maximum demands and shape of the daily load curve, involve many unknown factors which can be estimated only by the application of good judgment. For example, the diversity factor is one of the most important elements in utility engineering, and yet it is based entirely on the habits of the people. The diversity of load on the ordinary power system serving all the requirements of the community normally results in the use of the same system capacity successively for the domestic requirements in the morning, transportation from home to work, office and mill requirements during the day, transportation home at night, and domestic and recreation requirements during the evening.

THE economic problems of the industry are of pressing importance. All of the major public utilities have reached the stage of intensive development where economic pressure is apparent, and it is most essential to get the greatest possible value out of every dollar spent. Contrary to the general impression, all of the utilities today are operating under highly competitive conditions, which further emphasize the necessity for clear understanding and accurate solutions of the economic problems.

In the power industry, for example, economic balance between fuel efficiency and first cost of a steam power plant; between steam and hydro plants; economic development and use of interconnections between systems; efficient operation of power plants; proportioning of first cost and losses in lines and stations; determination of amount of investment permissible to serve a given block of business; determination of costs of the various classes of service, are a few of the problems in economics with which the business man engineer is confronted. The generation and distribution of electrical energy is an engineering problem throughout. It naturally becomes the engineer's job to work out for management the proper economic solutions of the various problems. He should, therefore, have a knowledge of practical as well as theoretical economics.

THE requirement that the engineers be able to deal successfully with other men has become of rapidly increasing importance in recent years, during which it has become necessary to develop great organizations to handle efficiently the enormous businesses that have grown up. When a public service company becomes as large as the major companies of today, it is not possible for the manager to carry the details in his own mind, nor is this possible even for the heads of the major departments. Thus a transaction is seldom handled completely within one unit of the organization. Hence no individual in the organization can obtain a complete result working by himself but rather, after contributing his own portion to the transaction, he must secure the co-operative action of a number of other persons in different departments. Team work thus becomes essential, and if a man is to be successful in a great organization of this kind, he must work with the team.

This development of organization has made it necessary for the engineer who would be successful to extend his interest and knowledge substantially beyond the field of technical analysis and understanding. It thus becomes desirable that, supplementing the fundamental technical education, the engineering student should give some thought to developing along the supplementary lines which, in the present day of great organization and co-operative action between men, are absolutely necessary to success. The most essential of these are as follows:—

*a—Report Writing*—The average engineering graduate, early in his practical career, is confronted with

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the necessity of presenting the results of his studies and investigations in concise, logical report form. These reports require a considerable knowledge of English composition and, judging from the average young engineer, more time than at present could well be spent in the technical school in studying English composition and report writing. This could well be supplemented by some training in public speaking.

*b—Salesmanship*—Throughout the engineer's experience he will find it necessary to sell his ideas to some one in order that they may materialize. Also it often becomes necessary to solicit the assistance of others in working out a project. This involves understanding of human nature in general and of each individual dealt with in particular, in order that the desired co-operation may be obtained. No matter how much authority exists through one's place in an organization, co-operation will not be obtained by strong-arm methods. Proper approach through persuasion is always necessary and to be successful the young engineer must attain skill in this branch of the game.

It is unfortunate that the student's work while in school must be so completely planned for him. In practical life he must lay out his own work, analyze his job and develop initiative. It is usually several months or even years before the graduate is able to re-adjust himself to the new attitude of working almost entirely on his own initiative.

A PROMINENT utility executive once said that there are three stages in a man's development. In the first he has supervision over things, in the second over things and men, and in the third over men only. Thus the engineer should advance from the first stage in which he deals only with technical problems, through the second, to the position of executive where his primary responsibility is supervision over men. In fact, the chief engineer of any large utility is more an executive than an engineer.

There never was as great an opportunity for the engineering graduate in the public utility field as at present. The power industry will spend more money in the next ten years than it has spent in any previous like period. The exacting demands for the highest possible grade of service and the economic pressure to get the greatest possible value out of every dollar spent make it necessary that particular attention be given to the recruiting and training of an adequate engineering personnel. The engineer who will qualify to grasp these opportunities will, however, be of the scientific business man type.

In conclusion, it is suggested that the engineer's training as a scientific business man should start while he is in engineering school; and that the best results will be obtained through more intensive study of English composition and report writing, and by giving attention to economics and salesmanship.

E. C. STONE,
System Development Manager, Duquesne Light Co.

**Relations Between Central Station Engineers and Prime Mover Manufacturers**

Present-day turbines embody something more than merely improved material and the higher grade of workmanship made possible by shop refinements. Their designs show the effect, as well, of broadened outlook on the part of the turbine engineer, who has come to realize that his ideals can be achieved with economic results which are satisfactory to the central station operator and also to his own commercial department. This is reflected in greater simplicity of structure and arrangement and in improved appearance. In this issue, a brief account is given of the history of the changes in practice which have determined the character of some of the latest designs of central station turbines.

An important factor in the economic progress of central station prime movers is the better understanding which has lately developed between the central station operators and the designing engineers of the manufacturers. This is especially evident in the tolerance which is being displayed by the executives and operating staffs of the central station companies when trouble develops with new equipment after installation.

There is a growing spirit of co-operation between operator and builder which may well be put to its fullest use. This is in the matter of preparing preliminary designs for new equipment, with full complements of efficiency and price figures. When a new project is being investigated, many studies are usually required on very short notice, in order to determine which arrangement is best suited for the particular operating conditions. If this preliminary information is to be of material assistance to the plant constructor, it must be accurate. Likewise, the machinery builder, not knowing which proposition will be accepted, must be fully prepared to build and deliver within a specified time limit, the unit represented by any one of the preliminary studies; and to guarantee the estimated efficiency and price. Consequently, these preliminary studies become, in due course, actual design. It is, therefore, essential that the designing engineer recognize his responsibilities during the negotiation stage.

The standard of this preliminary work can be maintained at a high level only by discouraging any changes in the guaranteed efficiencies and in the delivery and cost estimates after an order has been received, unless new requirements have been introduced by the purchaser which warrant reasonable modification; and it is here that the operator and the plant constructor might co-operate with the manufacturer to the mutual benefit of all concerned.

The real objective toward which these interrelated activities are directed is the production and distribution of cheap power. Progress will best be insured by continued improvement in relations between the turbine builders, plant constructors and plant operators.

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# Selection and Application of Induction Voltage Regulators

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WITH the growing complexity of electrical power transmission systems and the greater distances over which power is being transmitted, the problem of maintaining the desired voltage at the point at which the power is to be used becomes correspondingly more difficult. In order that the transmission copper may be worked at an economic current density, it is evident that the distance from the point of voltage regulation to that of the most remote outlet must be relatively short; the greater the current density and the closer the voltage regulation required the shorter this distance must be. With distribution systems covering large areas, it is immediately evident that some means is required by which the voltage may be controlled from some desirable point and with sufficient ease and rapidity to follow the general load change. These requirements are all met, for the alternating-current system, by the induction voltage regulator.

When voltage control is obtained with the voltage regulator by controlling the amplitude or direction of the voltage generated in a winding which is connected in series in the line, it is not necessary to open or

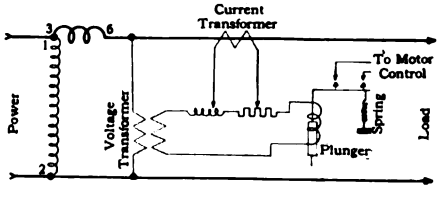
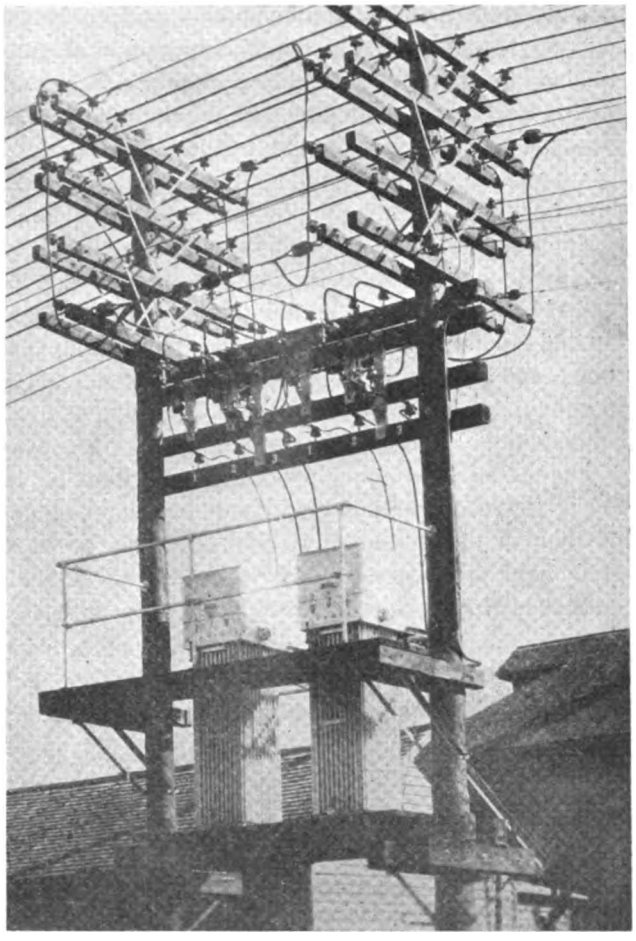



FIG. 1—A SCHEMATIC DIAGRAM OF A REGULATOR WITH A RELAY AND COMPENSATOR

close any circuits during the regulating operations. Hence no line disturbance is created which might result in voltage surges. To this fact is largely due the great advantages of the induction voltage regulator over other types of voltage regulators for almost all requirements. Smooth voltage regulation is necessary for incandescent lamp loads since a very small change in voltage, made suddenly, is readily noticeable in blinking of lights. Considerable voltage change can be made, however, without being objectionable or even noticeable if several seconds are used in making the change. Close automatic control of voltage is quite readily obtained where the voltage control is smooth, but presents serious difficulties if the voltage is changed in



**A typical outdoor induction regulator installation consisting of two single-phase regulators regulating two single-phase 2300 volt circuits. These regulators are rated at 46 kv-a, 60 cycle and 10 percent voltage regulation.**

steps, even though they be small. This can be readily appreciated by considering a regulator controlled from a relay which is operated from the line voltage. When contact is made at one extreme position of the relay, the voltage suddenly swings to the other extreme and unless the relay is almost perfectly damped, hunting or pumping will result.

In Fig. 1 is shown a schematic diagram of connections of a regulator with relay and compensator for automatic control, the compensator providing compensation for line drop on the load side of the regulator. The primary or exciting winding of the regulator is represented in Fig. 1 by winding 1 2, and the series or regulating winding is represented by 3 6. On the primary or voltage relay, the weight of the iron-core plunger is counteracted by the spring and the action of the solenoid on the plunger. As the voltage becomes low the plunger lowers, thus closing the contacts which control the circuit of an operating motor to move the regulator to a raise or boost position. In the same way if the voltage becomes too high the regulator is moved to a position to lower the voltage. The operation of the voltage relay acting on the regulator, therefore, is to maintain the voltage constant on that part of the circuit in which it is connected.

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By introducing a resistance and reactance in the operating circuit of the primary relay and circulating a current through these from a current transformer, it is possible to add a voltage component in this circuit which is dependent upon the load on the circuit. The series resistance is high, relative to the other impedance in the relay operating circuit, so that the current in it is practically in phase with the line voltage. The resistance and reactance in the compensating circuit can be adjusted to be proportional to those of the line between the regulator and the point at which the voltage is to be constant. The ratio of the compensator resistance and reactance to those of this section of the line should be made the inverse of the current-transformer ratio. This makes the voltage component in the compensating winding proportional to and of the same phase relation relative to the relay operating current that the main line drop is to the line voltage; thereby making it possible to hold the desired value of compensation at any power-factor of the load.

There are two distinct types of induction regulators in common use, the single-phase and the polyphase. While the general construction and appearance

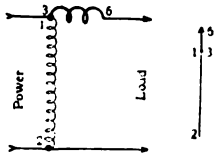


FIG. 2—CONNECTIONS AND VECTOR DIAGRAM OF A SINGLE-PHASE REGULATOR

of the two types are somewhat similar, the electrical operations are quite different and an understanding of these is essential for their correct application.

The electrical operation of the single-phase regulator may be likened to that of a single-phase transformer on which the number of turns of the secondary winding can be varied at will. While the number of turns on the secondary of the regulator is not changed, the same effect is obtained by rotating one member relative to the other so that only a portion of the main field flux is cut by the secondary winding. It may be turned far enough to reverse the direction of the field flux through it and completely reverse its induced voltage. Thus it is possible to buck or boost the voltage by the capacity of the regulator. When the secondary is at right angles to the main field or in the neutral position the secondary voltage is zero. In the same manner as with the variable secondary transformer, the secondary voltage is always either directly in phase with the applied voltage or 180 degrees from it. In Fig. 2 is shown the schematic connection and vector diagram of the single-phase regulator.

In the polyphase regulator, the windings are distributed and produce a rotating field as in the polyphase motor. The rotating field generates a constant voltage in the secondary winding and by rotating one member relative to the other, the phase relation of the secondary voltage to that applied to the primary may be controlled. This adjustable phase relation is used to produce the desired voltage change on the regulated side. Fig. 3 illustrates the method of connecting and the vector diagram for the polyphase regulator.

In the polyphase regulator, as in the polyphase motor, a component of current flows in the primary winding, balancing the ampere turns of the load cur-

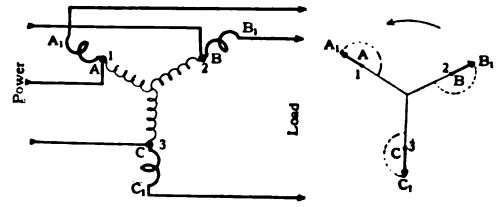


FIG. 3—CONNECTIONS AND VECTOR DIAGRAM OF THREE-PHASE REGULATOR

rent in the secondary and at 180 electrical degrees from it. As the primary is rotated to obtain the desired vector relation of voltages, the load component of current in the primary rotates likewise and with one direction of phase rotation this component will oppose the exciting current as the neutral position of the regulator is approached. If the phase rotation of the applied voltage is reversed, this load component of current in the primary adds to the exciting current in the primary winding and thus greatly increases the loss in the primary winding and may cause overheating. It is quite important, therefore, in installing a polyphase regulator that the phase rotation be such as to give the low value of the primary loss. The vector relation of currents with a unity power-factor load and the regulator in neutral position with the correct phase rotation is shown in Fig. 4. The corresponding current relations with incorrect phase rotation are shown in Fig. 5.

The direction of phase rotation may be checked on any installation of a polyphase regulator by measuring the current in the primary circuit under the two conditions of rotation. The most favorable condition for doing this is with a load approximately one-third or one-fourth the capacity of the regulator and having a high power-factor. Under this condition, as the

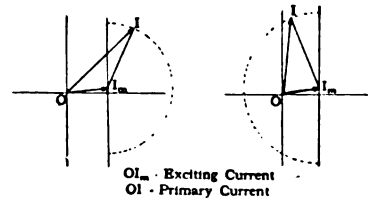


FIG. 5 FIG. 4

FIG. 4—CORRECT PHASE ROTATION OF A POLYPHASE REGULATOR
FIG. 5—INCORRECT PHASE ROTATION OF A POLYPHASE REGULATOR

regulator approaches the neutral position, if the phase rotation is correct the current in the primary of the regulator will become very low or almost zero. If the phase rotation is incorrect, the primary current will become, at the neutral position, almost double what it was in the maximum buck or boost position.

With these facts in mind, one of the first points to be considered in the application of induction regulators is whether to use the polyphase or the single-

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phase types where two or three-phase circuits are to be regulated. In general, the cost per kv-a of the single-phase regulator is lower than that of the polyphase regulator for similar ratings. Similarly the losses for the single-phase regulator will usually be found to be lower than those for corresponding ratings of the polyphase type. When single-phase regulators are to be used on polyphase circuits, they may be connected as illustrated in Figs. 6, 7 and 8, three-phase circuits being assumed.

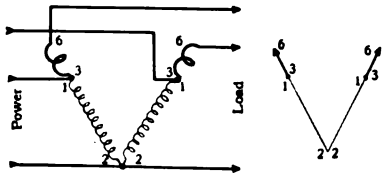


FIG. 6—CONNECTIONS AND VECTOR DIAGRAM OF TWO SINGLE-PHASE REGULATORS IN OPEN DELTA

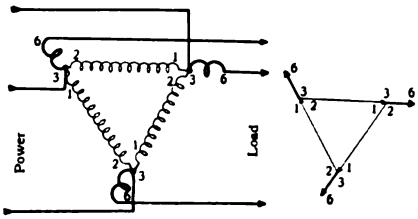


FIG. 7—CONNECTIONS AND VECTOR DIAGRAM OF SINGLE-PHASE REGULATORS IN CLOSED DELTA

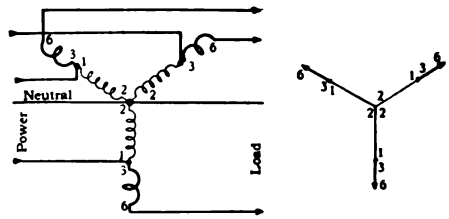


FIG. 8—CONNECTIONS AND VECTOR DIAGRAM OF SINGLE-PHASE REGULATORS IN STAR

As shown in Fig. 6, two regulators may be connected in open delta, each regulator being controlled by a separate set of auxiliaries. With this connection no phase shift is caused on the regulated part of the circuit and a certain amount of individual phase control is available. The absence of phase shift may be important if interconnected circuits are involved and the individual control of two of the phases is of advantage, as where the load may be unbalanced. The secondary voltages are of a phase relation which does not take advantage of the full capacity of the regulators, the rated kv-a being approximately fifteen percent greater than the available regulating kv-a. Due to the decreased capacity and the smaller units, this type of connection is about on a par with the three-phase regulator as concerns cost and performance. The points to be considered, therefore, between these two arrangements are: desirability of absence of phase shift; balance of load between phases; space available, whether two small units can be accommodated better than one larger; less maintenance for one unit than for two; flexibility of equipment where units may be moved from one location to another. The total percent regulation of the circuit with the two single-phase regulators in open delta will be the same as that of one regulator relative to its primary.

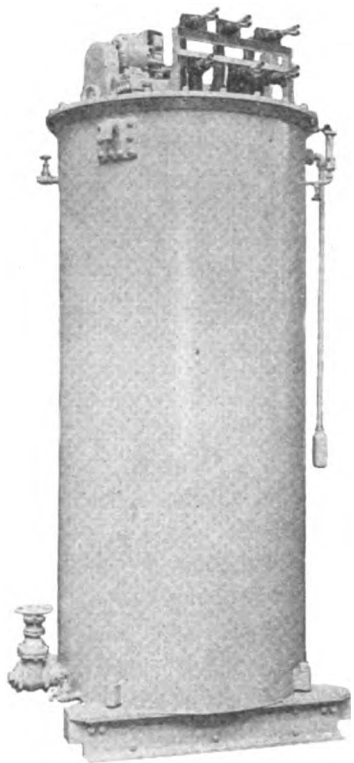

FIG. 9—A LARGE, HIGH-VOLTAGE POLYPHASE REGULATOR

This regulator is built for 12 500 volts, 1080 kv-a, three phase, 60 cycle indoor service. The flow indicator for the water cooling system can be seen extending half way down the right side of the tank.

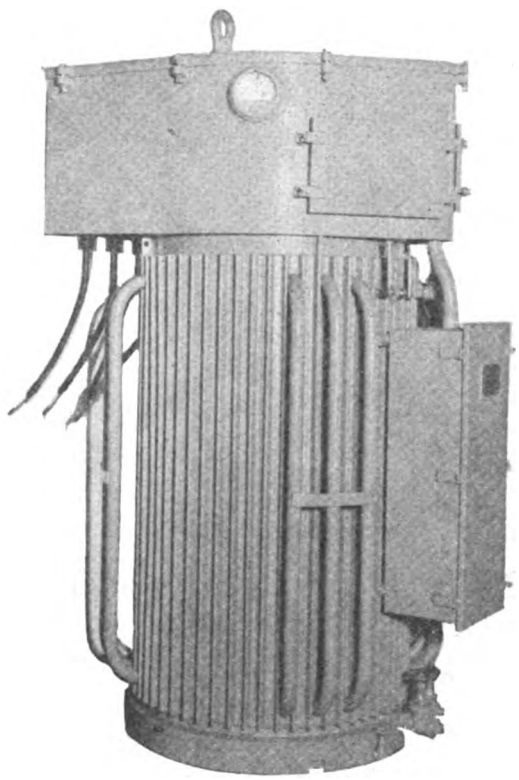

FIG. 10—A MODERN, THREE-PHASE REGULATOR FOR OUTDOOR SERVICE

This is a 72 kv-a, 4150 volt, four pole, 50 cycle, 10 percent regulator. The steel box at the side houses the compensator, control switch, and the line relay. The meter at the top indicates the position of the rotor. The three potential transformers, current transformer, and operating motor are enclosed on the top of the regulator to protect them from the weather. All the high-voltage parts inside the housing are separated from all low-votage parts by a grounded steel barrier so that the low-voltage parts may be worked on with perfect safety.

Three single-phase regulators may be connected in delta as shown in Fig. 7. This type of connec-

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tion gives a slight shift in phase on the regulated side and allows individual control of all three phases. The smaller units may increase the cost for this type of installation, over the open-delta type particularly where small capacities are involved. Aside from these points, the relative advantages of this arrangement of single-phase regulators are much the same as for the open-delta arrangement.

It is sometimes expected to use single-phase regulators in open delta as an initial installation and add the third regulator to take care of the increased load. This cannot be done, however, since the addition of the third regulator increases only the percentage of regulation and not the current capacity. With three ten-percent regulators connected in this way, the total regulation will be approximately fifteen percent.

For grounded neutral systems, or where a neutral connection is available, three single-phase regulators can be connected in a three-phase circuit with their primary windings in star as shown in Fig. 8. This type of connection has the advantage of no phase shift, individual phase control, and full capacity available.

At the present time single-phase regulators are available in capacities up to approximately five hundred kv-a. If quiet operation is an important consideration, better results are likely to be obtained with three-phase regulators in the larger sizes. Three-phase regulators have been built in sizes up to seventeen hundred and fifty kv-a, and larger sizes can be built if required. The highest voltage which can economically be used directly on the regulator windings is fifteen thousand volts on the largest sizes. In smaller ratings, the maximum economic voltage is reduced. This value for either single-phase or three-phase regulators may be found from the equation:

$$V = \frac{15000}{1 + \frac{75}{Kv\text{-}a + 8.5}}$$

The maximum current per terminal which can be handled economically is also limited, due to the distributed winding construction commonly used and may be found for either single-phase or three-phase regulators from the equation:

$$A = \frac{3000}{1 + \frac{100}{Kv\text{-}a + 5}}$$

The values found from these equations are not fixed and definite but represent usual practice and any contemplated regulator application to larger voltages or current should receive special consideration. For values above those that can be applied directly to the regulator, transformers may be used to step down the voltage or current.

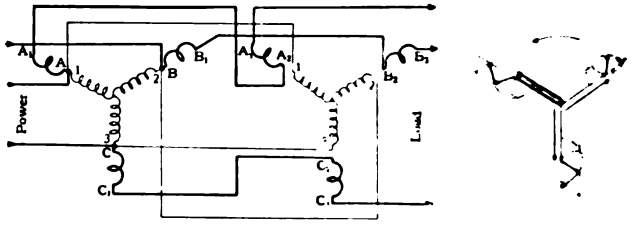


FIG. 12—CONNECTIONS AND VECTOR DIAGRAM OF DUPLEX REGULATOR

On a single-phase line of considerable length and moderate capacity with a concentrated load area near the end, a single-phase regulator could be installed near the load and controlled to maintain the voltage constant on the load, the regulator correcting for line drop between the power supply and the regulator. The regulator may be for outdoor service and if of small capacity may be mounted on a pole. For such an application, the compensator and current transformer can be omitted.

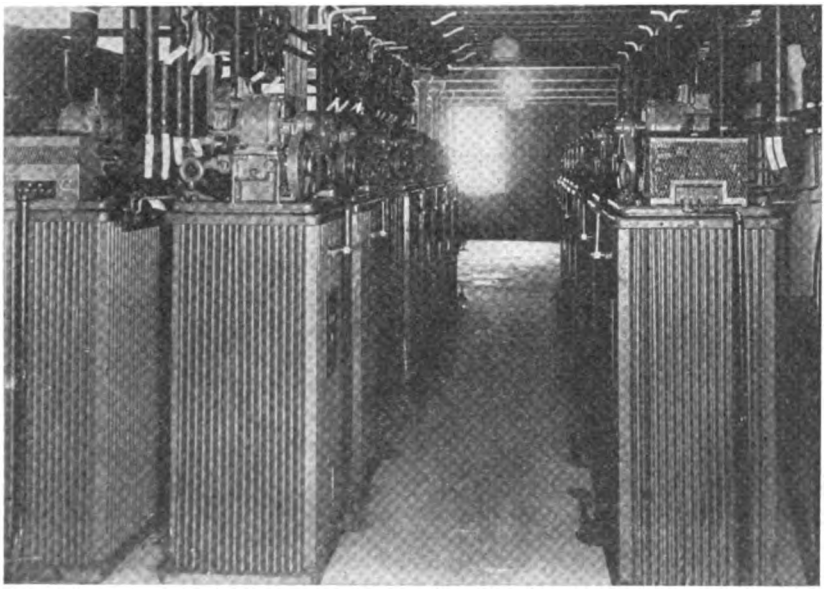

FIG. 11—A TYPICAL INSTALLATION OF SINGLE-PHASE REGULATORS IN A GENERATING STATION

A common distribution system is one in which power at high voltage is supplied to local substations and from these by radial feeders to the various load points. If the feeder lines are comparatively short, the regulators would be housed in the substation and would be of the indoor type. If the loads on the various feeders are subject to independent variation, individual regulators for each feeder should be used and should be equipped with compensators which control the regulators to maintain a constant voltage on each feeder near the center of the load.

The primary or exciting winding of the regulator can be connected either on the regulated (load) side or on the power side. The connection should be made to the side on which the average voltage will be lower, to be determined from the load curve. If the

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load is chiefly lighting with maximum requirements a few hours per day and small load the remainder of the time, a considerable saving in iron loss may be made by connecting the regulator primary on the load side where the regulator voltage is at a low value the greater part of the time. On the other hand, if the load factor is high, the regulator will be in a boost position a greater part of the time and hence the power side will have the lower average voltage and the primary of the regulator should be connected there. The iron loss varies approximately as the square of the voltage applied on the primary of the regulator, so the side of the regulator on which the r.m.s. voltage is lowest through a load cycle is the one best suited from which to excite the primary of the regulator. The total buck and boost capacity of the regulator is the same for either connection.

Where large concentrated loads are supplied, or where the feeders are short with evenly divided loads, bus regulation is usually employed. This allows the use of large regulator units with corresponding saving in the first cost and losses. Three-phase regulators will usually be found most advantageous for this method due to the smaller number of units necessary with correspondingly less auxiliary equipment and less maintenance.

Loop circuits and secondary networks introduce new factors to be considered in the application of induction regulators. If different three-phase regulators in the same interconnected system are controlled independently, a difference in the phase shift caused by different positions of the regulators may cause undesirable circulating current. For such applications, single-phase regulators are most commonly used, although if for some reason it is desirable to use three-phase regulators this can be done by the use of duplex regulators which consist of two similar regulators with their secondary windings in series and connected to give zero phase shift, illustrated as to connection and phase relation in Fig. 12. The two regulators connected in series must have their operating mechanisms mechanically coupled together in order to maintain the correct relative phase relation.

When two or more independently controlled regulators with compensators are used on circuits which are interconnected or paralled near the regulators, so that the impedance of the circulating current circuit is low, it is necessary to provide some means of stabilizing their action. If this is not done, as one regulator gets a higher load than the others it raises the voltage of that circuit thus increasing the current still further and the system is unstable in much the same way as compound generators in parallel. The simplest method of overcoming this difficulty is to connect mechanically the operating mechanisms of all the regulators on the circuits which are in parallel, thus keeping them all in the same relative buck or boost position so that the load division is controlled by the impedance of the individual circuits.

The points of interconnection may be some distance from the regulators in which case it may be desired to obtain some degree of individual operation. This is sometimes done by interconnection of the current transformers so that each regulator will not

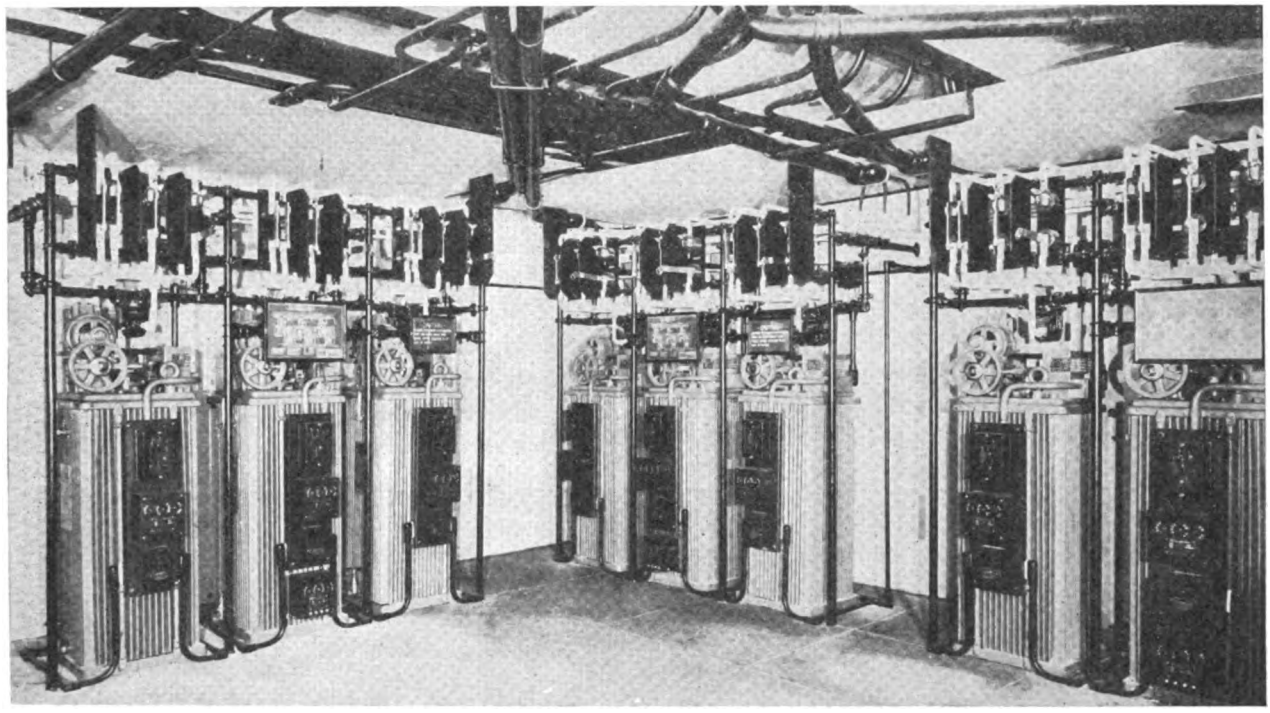

FIG. 13—AN APPLICATION OF SINGLE-PHASE INDUCTION REGULATORS TO THREE-PHASE, FOUR-WIRE CIRCUITS

This is a very neat installation of average size regulators in a generating station basement. The neutral compensator for the currents in the fourth wire can be seen near the bottom of the middle regulator of each group.

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be controlled solely by the current through its own circuit. Such connections should be worked out and adapted to the particular conditions involved.

There are many cases of interconnected circuits where the point of interconnection is a considerable distance from the regulator and the impedance to the circulating current is quite high. In such a case, if the impedance drop in the circulating current circuit due to a given value of current is greater than the voltage change produced by one regulator due to the same value of current flowing through its current transformer, then a stabilizing factor is introduced, and the regulators in the system may be controlled independently as though the system was not interconnected.

There are many cases where it is desirable to obtain smooth voltage control without interruption of the load on individual units or installations. Among these may be listed testing sets, laboratory equipment, furnaces, ovens and heaters. Automatic control can usually be developed to maintain temperatures and heat cycles accurately. For such applications any range of voltage may be obtained from zero to the maximum required, limitations in current and voltage capacities being kept in mind.

# Recent Developments in the Design of Impulse-Reaction Steam Turbines

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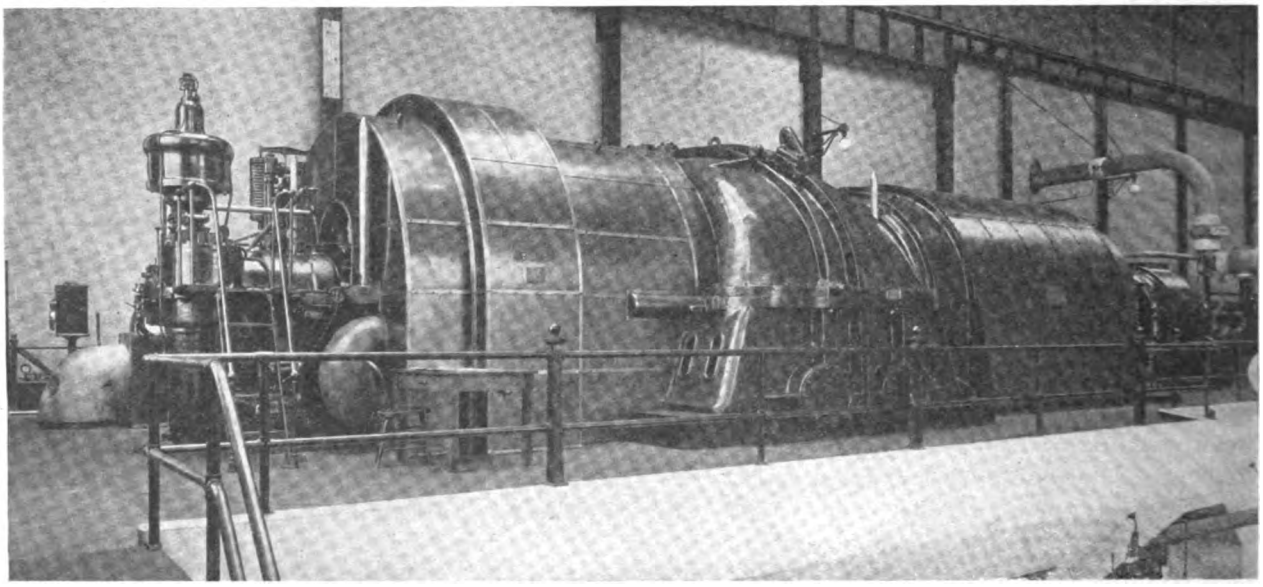
THE outstanding characteristic of modern turbine design is the rapidly increasing capacity of single-cylinder units. The standard single-cylinder, single-flow design is at present used for ratings up to 65 000 kw with four stages of feed heating. The Rankine Cycle efficiencies obtained vary from 75.5 percent for a 15 000 kw unit to 79 percent for the 65 000 kw frame. These are average figures which may be expected with operating conditions of 350 pounds steam pressure, 725 degrees F. total temperature, and 29 inches vacuum. They are taken at best-point loads of about 80 percent of rating. The generator losses are included. For capacities in excess of 65 000-kw, the cross-compound construction is still to be preferred. A rating of 300 000-kw can easily be obtained with a three-shaft machine if the demand should arise. With the cross-compound construction, better efficiencies are to be expected than are possible with single-cylinder designs.

In addition to the greater capacity per unit, and the better efficiencies of modern turbines, a marked improvement is noted in the reduction of weight and floor space required. For example, in 1914 the typical central station generating unit weighed 42.5 lb. per kilowatt of rating and required 59 sq. ft. of floor space per thousand kilowatts. In 1922, the corresponding figures for a typical machine were 34 lbs. per kilowatt and 39 sq. ft. of space per thousand kilowatts. Today. a 165 000-kw unit, actually under construction, weighs only 14.9 lb. per kilowatt and requires only 16 sq. ft. of floor space per thousand kilowatts. It must not be concluded, however, that this reduction in weight is



A 30 000 KW, 1800 R.P.M. TURBINE-GENERATOR INSTALLED AT THE REEVES AVENUE PLANT OF THE VIRGINIA ELECTRIC LIGHT AND POWER CO., NORFOLK, VA.

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necessarily accompanied by any proportional reduction in cost. The modern high-blade-speed construction is inherently more expensive to build. Furthermore, it is necessary to use more costly materials which, in turn, require more expensive manufacturing processes.

### EFFECT OF DESIGN ON COST

IN GENERAL, the design of any central-station turbine begins with the determination of dimensions of the last row of moving blades. The value assumed for the area of this last row is an important regulating factor in the cost. Having assumed the annular area of the last blade row, the commercial rating of the unit must be determined entirely by a study of the station for each particular job. For example, with a standard 1800 r.p.m. turbine having an annular area of 44 sq. ft., it can be shown that the rating can be varied economically from 20 000 to 35 000 kw, depending on the load factor, daily and annual load curves, fuel cost, etc. In modern practice, the annular area of the last row of blades per thousand kilowatts is found to vary from about 1.25 to 2.50 square feet.

While the reduction of the annular area of the last row of low-pressure blades is an important factor in keeping down the cost, a practical limit is soon reached with high-vacuum turbines, because of the leaving losses due to the kinetic energy remaining in the steam which is rejected to the condenser. With average steam conditions, four-stage feed heating, and 29 in. vacuum, a last blade row annular area of two sq. ft. per thousand kilowatts of rating will give a corresponding leaving loss of approximately 1.7 percent. When the annular area per thousand kilowatts is reduced to 1.5 sq. ft., this leaving loss increases to about 3.8 percent. This, at first, appears to be a serious depreciation but, contrary to what might be expected, the larger machines, even of the multi-cylinder type, are being designed with progressively smaller annular blade areas in order to keep the costs within reasonable limits. The improved efficiencies in the high-pressure zones obtained by the natural reduction of windage, friction, and leakage as percentages of the total work, permit the larger machines to be designed with progressively higher overall efficiencies in spite of the increased leaving loss.

### FEATURES OF DESIGN CONTRIBUTING TO THE IMPROVED EFFICIENCIES

INCREASED tip speed in the last row of low-pressure blades has contributed largely toward the improvements in overall economies. It is the natural aim of the designer to employ the maximum allowable rotative speed for a given capacity because the weight and, for similar designs, the cost will approach their minimum values. Geometrically similar turbines, whose rotative speeds vary inversely as the dimensions, will have approximately equal efficiencies. Although the capacities vary as the squares of the dimensions, the weights vary as the cubes, which fact indicates a tendency for the weight per kilowatt of rating of nearly similar turbines to vary directly as the dimensions. Actual cost records confirm this theory sufficiently well to lead to the prediction that there will not be a tendency toward the general adoption of turbine speeds lower than 1800 r.p.m., but rather an invasion of the central station field by 3600 r.p.m. machines.

With parallel-flow turbines, it was formerly held inadvisable to employ low-pressure blades for which the ratio of mean diameter to active length was less than 5.0. In 1921, low-pressure blades with variable inlet angles were introduced to permit the use of lower ratios of mean diameter to active length. With this type of blade, it was still possible to secure reasonable fluid-flow conditions in spite of the greater variation in peripheral speed from the blade tips to the base sections. The successful performance of this new type of blade has led to a progressive reduction in the ratio of mean blade diameter to active blade length from 5.0 to 3.3. Another important development was the introduction of tapered blades for use in the low-pressure end. These replaced the old parallel-section blades and at once made possible a substantial increase in blade area at a given rotative speed with the same working stresses.

The following comparison shows the remarkable improvements which have been accomplished by means of the above developments. Prior to 1921, the maximum last row blade annulus was 25 sq. ft., which required 15 inch blades on a 62 inch diameter drum, with a blade tip speed of 723 feet per second at 1800 r.p.m. and with a 5.1 ratio of mean blade diameter to active length. Sufficient steam could be passed through this annulus to give a total unit capacity of 12 500-kw at the market efficiencies with 29 inches vacuum. These proportions allowed 2.0 sq. ft. of last row annular area per thousand kilowatts of rating.

In 1921, the forerunner of the modern high-blade-speed turbines employed 23.5 inch blades on a 62 inch diameter drum, which gave a blade tip speed of 865 feet per second at 1800 r.p.m. The annular area was thus increased from 25 to 44 sq. ft. by the use of tapered blades with the variable inlet angle, and the ratio of mean blade diameter to blade length was reduced to 3.7. These proportions made it possible to pass sufficient steam at 29 inches vacuum to give a rating of 25 000-kw at the desired efficiencies. The annular area per thousand kilowatts was 1.76 sq. ft.

In 1925, these same principles were carried further in turbines using 27 inch blades on a 70 inch diameter drum, which gave an annular area of 57 sq. ft., and a blade tip speed of 976 feet per second at 1800 r.p.m. with a diameter to length ratio of 3.6. This design passed sufficient steam to develop 35 000 kw with satisfactory economy, thus giving an annular area per thousand kilowatts of 1.63 sq. ft.

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Present designs include improved constructions which permit the use of 34-inch blades on a 78-inch base diameter, giving an annular area of 83 sq. ft. with a blade tip speed of 1147 feet per second at 1800 r.p.m. and a 3.3 ratio of mean diameter to active length. These blade proportions can be used for capacities up to 65 000 kw, which gives an annular area of 1.28 sq. ft. per thousand kilowatts of rating. Thus it is seen that the modern construction with high blade speeds is responsible for economic results of great importance, particularly a marked reduction in weights and floor space required. Such rapid increases in capacities, blade lengths and rotor diameters as noted above have necessarily involved difficult problems in metallurgy, manufacturing processes, and construction.

In the discussion of the effect of the introduction of high blade speeds on turbine performance and costs, the comparisons are made between single-flow reaction elements. The multiple-exhaust blading principle, which permits the use of smaller rotor dimensions for a given capacity, is not included in any of these comparisons.

THE ROTORS which carry the blades have undergone equally important changes. In the earlier impulse-reaction machines, the 15-inch blades were mounted on cast or forged steel discs with overhanging rims, while the high pressure blades were carried on relatively thin steel drums. With the introduction of the 23.5-inch blades, the overhanging rims and thin drums disappeared, being replaced by rotors of practically solid construction. The 27-inch blades introduced new problems in rotor stresses which, in one design, resulted in the last three rows of moving blades being carried on discs machined integral with the solid rotor, with sufficient space between them to secure the desired stress distribution. Up to this time, all large rotor parts had been made of 0.40 percent carbon steel.

The 34-inch blades referred to above necessitated major changes in both rotor construction and blade fastening. The low-pressure section of the new rotors consists of three solid discs, each carrying one row of blades, the discs being integral with the shaft extension. This low-pressure spindle end is now machined from air-quenched forgings of 3.5 percent nickel steel, thus permitting higher working stresses without a reduction of the factor of safety. The old T-root blade fastening is replaced by a new "side entry" type. The front and back surfaces of the curved blade roots are machined with grooves resembling a buttress thread, and the blades are assembled from the sides of the spindle discs in approximately axial grooves in the outer periphery.

In rotor design, one objective is the securing of an ultimate stability which will permit a unit to remain in service indefinitely, without the necessity of truing-up or rebalancing the rotating element. The new type solid rotors have shown exceptional stability, and there is apparently little danger of permanent distortion, even if blade rubs or similar disturbances should occur. Other important features in this construction are the reduced number of joints and the greatly increased bolt power. Main rotor bolts are now tightened with a definite stretch, so that the load on the compression faces of the joint is known within close limits. Central measuring holes are provided in the bolts, in which special depth micrometers are used to determine the original stretch of each bolt when assembled. It should not be concluded that these rotors are made solid to eliminate the cost of removing the interior, because such is not the case. The metal in these parts is worked up to the maximum safe stresses throughout.

The cylinder designs have been changed mainly because of the higher stream pressures and temperatures employed in recent years. Four-inch alloy-steel cylinder bolts are now quite common. These are given a definite stretch which is determined by means similar to those described above for the rotor bolts. This stretch is obtained by first expanding the bolts by means of electric heating elements inserted in axial holes, and then tightening the nuts to obtain the desired stretch, which is measured after the parts have returned to normal temperature. In addition to the stronger bolting, the general tendency has been toward narrower flange faces in order to increase the unit compressive stresses on the face of the joint.

High-pressure cylinders now are suported on sliding feet located near the horizontal centerline so as to permit expansion in any direction. Vertical keys are used at the cylinder ends to maintain correct transverse alignment. The same general principle is worked out in the low pressure cylinder structures in order to allow all parts to expand freely in all directions from the centerlines and thus eliminate distortion and misalignment. The bolted-in bearing pedestal at the high-pressure end has been definitely abandoned for large turbine work. The present type of pedestal is connected to the cylinder flexibly, so that, while precise axial and transverse alignment is maintained, the pedestal remains flat on its sliding feet under all operating conditions.

### BLADING STILL THE GREATEST PROBLEM

VIEWED from any angle, the blading stands foremost as the greatest problem before any turbine builder. Numerous improvements have contributed to the practical elimination of blade breakage. Blade widths for a given duty have been increased. Stainless steel is employed for rotor blades in the high temperature zones, and the present indications are that this material will ultimately be adopted for all rotor blades and for cylinder blades in zones of high temperatures or stresses. Stainless steel in suitable bar form is now available in adequate quantities, and processes have been developed to roll and fabricate it satisfactorily.

Considerable development has been necessary in the manufacture of the large rotor blades for the low-pressure zones. The port sections of these blades are forged to accurate dimensions, except on the edges,

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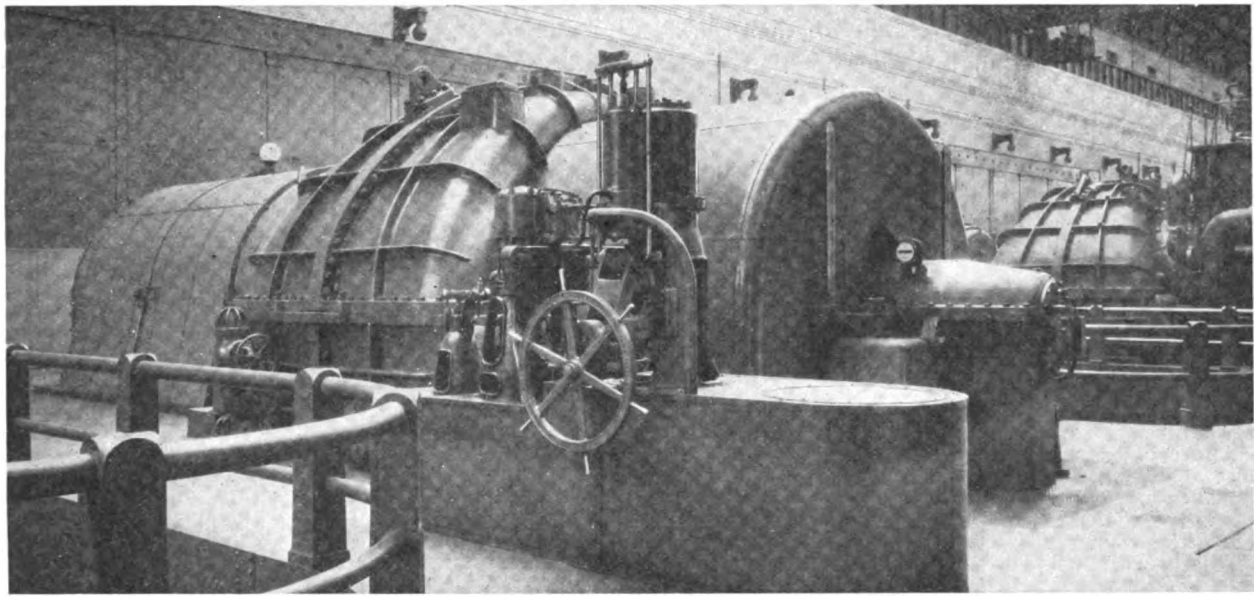
which are machined to thickness. At the present time, both five percent nickel steel and stainless steel are used as blade materials, but in the near future stainless steel will be adopted for all such work. With the increase of blade speeds, erosion of five percent nickel steel in the low-pressure zones has also increased. Future experience is expected to prove that the stainless steel will make possible the use of high blade speeds with less low-pressure blade erosion than before.

Other factors contributing to the increased reliability of blading are: improvements in processes, such as rounding of the blade edges, packing piece edges, lashing wire holes, etc. Direct research has demonstrated beyond question the value of careful attention to these matters. The average increase in fatigue resistance due to the rounding of the blade edges has been shown to be approximately 200 percent. The lashing of reaction blades has undergone numerous changes, such as, the location of the lashing wires to better advantage, an increase in the diameter of the wires, and the use of pure nickel as the standard lashing wire material.

The stainless steel which is now being used for blading is not stainless in the same sense as is implied when referring to cutlery steel. The stainless steel used for turbine blades will rust to a certain extent. Results of tests indicate that the erosion of the stainless steel used for turbine blades is only about 1/20 that of the five percent nickel steel. The superiority of this stainless steel has been demonstrated further by field experience extending over a period of three years, during which time it has shown excellent wearing qualities under severe service conditions. It must be borne in mind also that stainless steel blading is another important factor which increases the cost of turbine construction. The use of this blade material throughout in a 35 000 kw machine increase the total cost approximately ten percent. In addition to the increased cost of raw material, there are also more manufacturing operations and the increased wear on the tools used to work the harder material.



A 41 250 KW, 1800 R.P.M. TURBINE-GENERATOR INSTALLED IN THE COLFAX STATION OF THE DUQUESNE LIGHT CO., PITTSBURGH

### OPERATING CHARACTERISTICS

THE RESULTS of all these developments in design and construction must be measured, largely by the performance of the machines in operation. The rapid changes naturally have led to some field troubles which, in most cases, have been easily overcome. Those qualities which permit a large turbine to be started from rest quickly, to run indefinitely at any load it can carry, to operate alternately condensing and non-condensing without distress, and to withstand accidental shots of water from the boilers, come under the general term operativeness. It is only natural to expect that as turbines increase in size, greater care must be exercised when bringing them up to speed. The larger structures have higher heat inertia, and special precautions become necessary in order to avoid uneven heating and cooling which might result in excessive distortion and vibration. Much of the difficulty experienced with vibration during starting periods is due to the rotor being distorted by uneven cooling after the previous shut-down. Air circulation and rotor turning gears are being provided which eliminate this uneven cooling, and thus greatly decrease the length of time required for starting.

The stand-by service conditions which require turbines to operate for indefinite periods at full speed and no-load steam flow can be met without difficulty. So far as any other operating characteristics are concerned, the modern units should be as satisfactory from the operators' standpoint as the older types. The records of turbines of recent design now in service indicate that, in spite of the enormously greater concentration of power in single units, and the use of materials operated at higher working stresses, the reliability of central station machines will continue to increase.

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# Methods of Selecting Electric Elevators

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The object of this article is to call attention to the various features and characteristics of elevator service to be considered; to point out, in a few typical instances, the relative importance of these characteristics, and third, to outline the types of elevators that general practice has shown to be suitable for certain classes of buildings. Every installation, of course, requires individual attention and the following comments and tables should be considered as suggestions, to be supplemented by due consideration of the peculiarities involved in the particular job.

THE problem of specifying the right type of elevator has become an extremely important factor in the final efficiency of a building, especially in a congested district where as much of the building space as possible must serve a useful purpose. Architects, owners and building managers realize the increasing necessity of an intensive study of their elevator problems. After giving due consideration to the obvious requirements of safety, reliability and initial price, the most important items that affect elevator requirements are given in Table I. In any one type of building, some of the above features may be far more important than others and some of the items listed may be of no consequence.

TABLE I—FEATURES ENTERING INTO ELEVATOR SELECTION

| |
|---|
| 1—Passengers handled per hour. |
| 2—Interval of departure. |
| 3—Capacity. (Pounds, passengers or platform area). |
| 4—Speed of car. (Time to reach destination). |
| 5—Comfort of passengers. (Smooth operation, appearance of cabs, enclosures, etc.). |
| 6—Quietness of operation. |
| 7—Cost of operation. (Personnel). |
| 8—Cost of operation. (Material and power maintenance). |
| 9—Ability to withstand abuse and neglect. |

There are many methods of classifying buildings and likewise many different classifications of elevators. From the point of view of elevator service, all important installations are shown in Table II, Column A. In addition, the following less common elevator installations must occasionally be considered:—

Residences
Theater balconies and galleries
Bridge terminals
Elevated and subway stations
Towers and monuments

In the contemplation of any elevator installation in conjunction with Table I, the exact relative importance of the required characteristics is not as important as the provision that none of the essential features be overlooked in specifying the proper types of elevators.

For instance, in a high-class office building, every item in Table I should be carefully considered, with the possible exception of the last feature "Ability to withstand abuse and neglect." It is assumed that in a first-class office building competent maintenance men will be employed for the elevators.

On the other hand, it is obvious that in an apartment building, where the maintenance of an elevator is only incidental to a multitude of other janitorial duties, equipment must be installed that will function almost indefinitely without any more attention than an occasional oiling. In this type of building the "Passengers handled per hour" is seldom of importance while the "Quietness of operation" and the "Cost of operation (personnel)" should be thoroughly investigated. The wages of operators become a considerable item in the operating expense of an apartment building.

In a hospital the "Comfort of passengers" and "Quietness of operation" are very essential, while these features are often disregarded entirely in factories and garages.

In this way, each job should have thoughtful attention, not only by the architect and owner, but also by the elevator manufacturers, who must design and install their equipment in such a way that the elevator operation will meet the exact requirements of the installation.

Having considered the general features that are desirable in the various classes of elevator installations, some of the more specific questions, such as car speeds, capacities and control should be given attention.

The rated full speed of an elevator depends principally upon the type of building and height of travel of the car. Among other "Elevator fallacies" there is a rather common assumption that a high-speed elevator is better than a low-speed elevator for any application. In view of the fact that the initial cost, as well as the cost of power and maintenance, increases more than directly in proportion to the speed of the car, careful consideration should be given to determining the most satisfactory and economical car speed. Column B of Table II shows a reasonable speed of elevators for the various types of installations through the various ranges of floor travel.

Elevator capacities, usually rated in pounds, are of vital importance. If a car is too small for its average load, a great deal of time is wasted and poor elevator service results. On the other hand, if an elevator is larger than necessary, the extra investment in money, as well as the extra building space used, are direct losses. It is obvious that the power consumption of a large car is greater than that of a small car, regardless of whether the car is loaded or empty. Column C of Table II shows, for each type of installation, a range of capacities that have been found to be satisfactory. The average of these ranges may be considered as reasonable for contemplated buildings, the

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detailed service requirements of which have not yet been determined. For freight elevators, of course, the exact size and capacity of a car depends upon the material to be handled.

In Column D are shown the ranges of effective platform areas that correspond to the capacities shown in Column C. In determining these platform areas of passenger elevators, the allowable capacity per square foot varies from 70 to 100 lbs., depending upon the total capacity.

The electrical control of elevators is a subject that has recently come into great prominence with the advent of high buildings and more exacting standards of service. The terms used in describing the several methods of control are not consistent in different localities. Furthermore, various manufacturers often employ different trade names for the same or similar methods of car operation. Therefore, in order to make recommendations, or indicate the types of control that have proved satisfactory for various applications, a brief explanation is included of the most common methods of elevator operation.

TABLE II—ELEVATOR SPEEDS, CAPACITIES AND CONTROL METHODS

| A | B | | | | | C | D | E | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Type of Buildings | Car Speeds Feet Per Minute | | | | | Car Capacity Pounds | Floor Space Per Car, Sq. Ft. | Control Methods | | |
| Number of Floors | 2—4 | 5—8 | 9—14 | 15—24 | 25—50 | | | Most Desirable | Less Expensive | Least Expensive |
| 1 —Large Office Buildings, (Express) | | | 600 | 700 | 800 | 1500—2500 | 20—31 | C Sw, VV, AL | C Sw, VV | |
| 1a—Large Office Buildings, (Local) | | 400 | 500 | 600 | | 2000—3000 | 26—36 | C Sw, VV, AL | C Sw, VV | C Sw, Rheo |
| 1b—Small Office Buildings | 100 | 300 | 400 | 500 | | 1500—2500 | 20—31 | C Sw, VV | C Sw, Rheo | |
| 2 —Loft Buildings. (Combinations of Stores, Offices, Manufacturing Shops and Warehouses) | 100 | 300 | 400 | | | 1500—2500 | 20—31 | C Sw, VV | C Sw, Rheo | |
| 3 —Public Buildings. (Libraries, R. R. Stations, Post Offices, Administration Buildings, etc.) | 100 | 300 | 500 | 500 | | 2500—4000 | 31—46 | C Sw, VV | C Sw, Rheo | |
| 4 —Hotels (Passenger) | 100 | 300 | 500 | 600 | 800 | 2000—3000 | 26—36 | C Sw, VV, AL | C Sw, VV | C Sw, Rheo |
| 4a—Hotels (Service) | 100 | 200 | 400 | 500 | 600 | 1500—3500 | 20—40 | C, Sw, VV | C Sw, Rheo | |
| 5 —Apartment Hotels (Passenger) | 100 | 300 | 400 | 500 | 600 | 1500—3000 | 20—36 | Dual, Mult, VV | Mult, VV | Dual |
| 5a—Apartment Hotels (Service) | 100 | 200 | 300 | 400 | 500 | 1500—3500 | 20—40 | Mult | Dual | C Sw |
| 6 —Apartment Buildings (Passenger) | 100 | 200 | 300 | 500 | 600 | 1500—2500 | 20—31 | Mult | Dual | C Sw |
| 6a—Apartment Buildings (Service) | 100 | 200 | 200 | 300 | 400 | 1500—2500 | 20—31 | Dual | PB | |
| 7 —Department Stores | 100 | 200 | 300 | 400 | 500 | 2500—4000 | 31—46 | C Sw, VV, AL | C Sw, VV | C Sw, Rheo |
| 8 —Single-Line Stores | 100 | 200 | 300 | | | 1500—2500 | 20—31 | Dual | PB | C Sw |
| 9 —Hospitals (Passenger) | 100 | 200 | 300 | 400 | | 1500—2500 | 20—31 | C Sw, VV | C Sw, Rheo | |
| 9a—Hospitals (Service and Stretcher) | 75 | 100 | 200 | 300 | | 1500—3500 | | Mut VV | Dual, VV | Dual, Rheo |
| 10 —Factories and Warehouses (Freight) | 75 | 100 | 150 | | | 3000—20,000 | | C Sw, AL | Dual | C Sw |
| 11 —Garages (Passenger) | 100 | 200 | 300 | 500 | | 1500—2500 | 20—31 | Dual | C Sw | |
| 11a—Garages (Automobile Lifts) | 75 | 100 | 200 | 300 | | 4000—10,000 | | Dual, VV | PB | C Sw |

C Sw—Car Switch; VV—Variable Voltage; PB—Single party push button; Rheo—Rheostatic; AL—Automatic landing or levelling; Dual—Combination car switch and push button; Mult—Multicall or Collective.

### *Car Switch Control*

With this control, an attendant operates the car by means of a self-centering switch in the car. To this type of control there have been many refinements added. For instance, extremely smooth operation can be secured by variable voltage, which employs a motor-generator set for each elevator. By this method, the elevator motor is accelerated, decelerated and reversed by control of the generator field. Automatic landing or levelling is sometimes added to car switch control to save time otherwise required by the operator to make accurate landings. Still further refinements in the methods of automatically stopping and starting the cars, opening and closing the doors, synchronizing the cars by varying the car speeds, etc., are in process of development. Most of these features tend to eliminate the personal element and thus improve the elevator service.

### *Push Button Control*

With this control, an attendant is not required in the car. The movement of the car is controlled by push buttons in the car and in the corridors. The necessary safety features, such as car gates, emergency stop buttons, door locks and emergency call bells are always installed to make this type of elevator safe without the presence of an attendant. This control has also been called "Automatic Control" and in view of more complicated schemes recently developed which also employ push buttons, this type is sometimes called "Single Party" or "Single Call Push Button" control.

### *Dual Control*

This is a combination of car switch control and some form of push button control. Very often a keyed switch in the car is installed to operate a transfer switch on the controller, thus enabling an authorized person to change the control easily in the car.

### *Multicall Control*

There are many forms of this control, which is also called collector or collective control. Briefly, it is a push button control, capable of making the car respond to any number of calls, as it reaches the floors for which these calls have been registered. The variations of multicall control are more or less clearly indicated by the names applied, such as, "Two-Button", "Single-Button," "Corridor Down Only", etc.

Many other types of elevator control might be mentioned, but most of them are methods that are installed where initial price is the determining factor and for that reason are seldom entirely satisfactory. Hand cable control, for example, is a very simple control for low-speed work, but is dangerous when installed in such a manner that the control cable can be reached from the corridor. Hold-in-button, also called hold-down-button, or constant pressure control, requires the constant pressure on the button until the car arrives at the floor. The objection to this is obvious. Semi-dual, similar to the dual control except that no car switch is used, requires the operator to use the car push buttons during "car switch" operation.

In making recommendations for specifying controls to be used in various types of buildings, it would be impractical to designate arbitrarily certain styles of control for certain buildings. However, we may again assume average conditions, and on this basis, Column E, Table II, shows a satisfactory method of control for each type of installation, with at least one alternate to

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be considered under conditions where a less expensive or less elaborate elevator is satisfactory.

In the past there have been many influences brought to bear on the choice of elevators, that were entirely out of proportion to their value. For example, there are many prejudices in some localities against certain classes of elevators, because of the misapplications in these localities. Building competition has also created a demand for highly special and unique features in elevator practice, for their advertising value. In some cases these features actually decrease the elevator efficiency.

Various methods of elevator control and operation have been, and will be produced under various trade names. Many of these are exceedingly complicated and require very competent and experienced personnel to maintain the equipment. Therefore, if two different types of elevator equipment are equally satisfactory from the standpoint of elevator service, the advertising benefits secured by the more complicated and spectacular elevator may be more than offset by the reliable performance and the less costly maintenance of the other, more simple type.

# Relaying the 110 000 Volt System of the Edison Electric Illuminating Company of Boston

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Electrical Engineer,
Edison Electric Illuminating Co. of Boston

A HIGH-TENSION power transmission line is quite expensive, and must be protected by suitable relays in order to keep it in service whenever possible. Many relaying schemes have been devised but, as is to be expected, each has its limitations. The final system selected must necessarily be a compromise of the advantages and disadvantages, both from the engineering and the commercial standpoints. Local conditions will determine which features should be stressed.

The 110 000 volt system of the Edison Electric Illuminating Company of Boston, Fig. 1, was de-

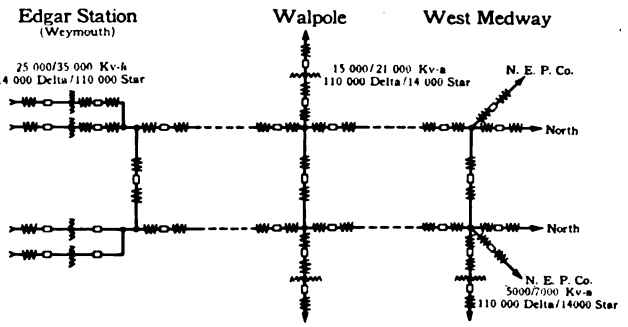


FIG. 1—THE CONTEMPLATED 110 KV SYSTEM OF THE EDISON ELECTRIC ILLUMINATING CO. OF BOSTON

signed initially for 75 000 kv-a, 400 ampere circuits running from the Edgar generating station at Weymouth, twenty miles to a switching substation at Walpole and thence ten miles to a similar station at West Medway. At that point connection is made to the New England Power System and provision left for extending the lines to form a possible high-tension ring around the city.

It is intended to have four 25 000/35 000 kv-a transformers (two per line) at Weymouth, two 15 000/21 000 kv-a transformers at Walpole, and one 5000/7000 kv-a unit at West Medway, where provision is made for future synchronous condensers. The higher ratings will be obtained by adding radiators to the transformers. All are arranged for future tap changing under load.

The requirements for these lines are that they may be operated:—

1—Both in parallel (tie circuit breakers closed).
2—Either line alone (tie circuit breakers closed or open).
3—Both lines independently (tie circuit breakers open).
4—Power flow in either direction.

The ideal relay system would allow the above operating procedure, have instantaneous and proper

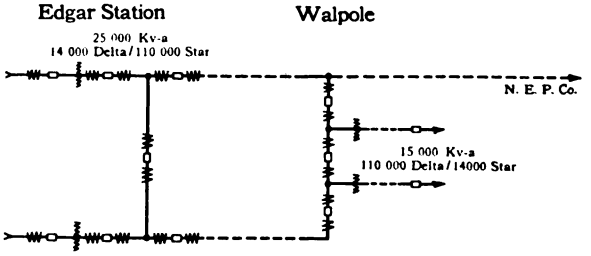


FIG. 1 (a)—THE PRESENT 110 KV SYSTEM

selectivity of the faulty line or bus sections, be unaffected by added stations, and give protection in case the first line of defense fails.

Preliminary consideration of various relaying schemes reduced the study to three general types;—

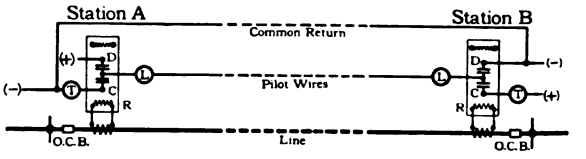


FIG. 2—SCHEMATIC DIAGRAM OF THE PILOT WIRE SYSTEM

*R*—Directional overcurrent relays (Successive timing).
*D*—Directional contacts.
*C*—Overcurrent contacts.
*T*—Line circuit breaker trip coils.
*L*—Instantaneous relays to reduce timing. These may short-circuit the time delay relays, torque compensators, or resistors in the voltage restraining elements.

pilot wires, impedance relays or cross-connected directional relays.

A new method of pilot wire application was devised, Fig. 2, which has selective-timing directional-

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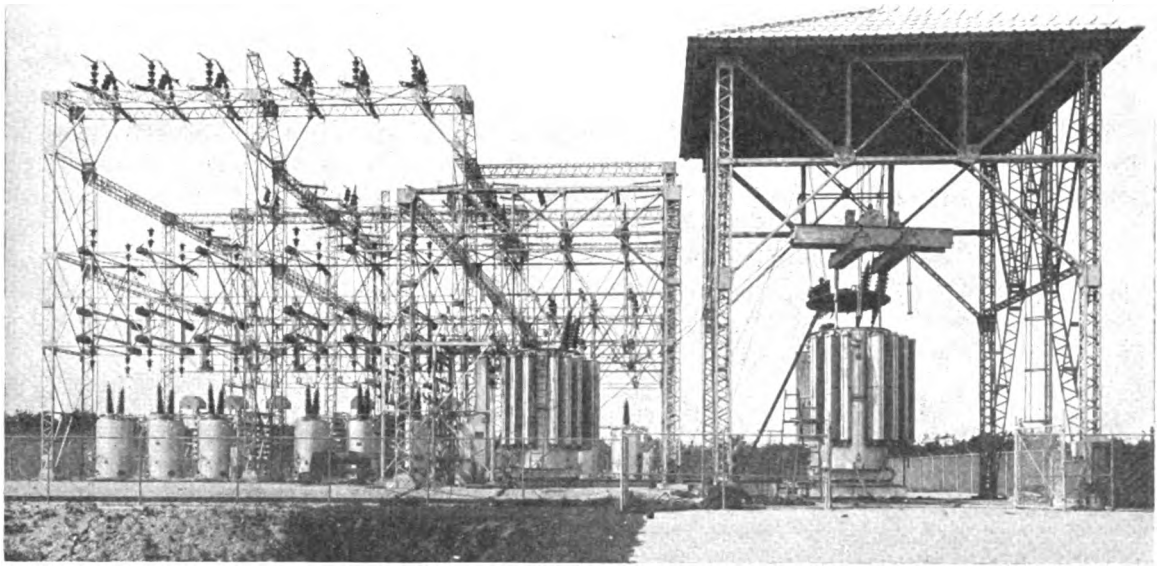

FIG. 3—WALPOLE RING STATION OF THE WEYMOUTH-MEDWAY 110 KV TRANSMISSION LINE
The transformers can be run along a track into the dismantling tower at the right for repairs.

overload relays at each circuit breaker, the directional elements being interconnected through the pilot wires to short-circuit the time-delay of these relays. Thus a fault would cause the directional elements at each end of the line section to swing in, thereby making these relays instantaneous, so that if the fault is sufficient to operate the current element the circuit breakers will trip. The system inherently has back-up protection, as the following line sections would operate after the normal time setting in case the first circuit breaker fails to open. Opening or grounding the pilot wire would not affect the safety of the system, as the relays could still operate after their time setting.

Induced surges would not cause improper tripping as the current elements are normally open. The only apparent disadvantage of importance is the relative high cost of the cable for the pilot wires.

The impedance relay in theory appears to meet the conditions. However, it was felt that difficulty might be met in obtaining the proper selectivity, due to the short lengths of line between stations, and to the probable small fault currents to be expected. Since the ground current would probably be less than the load current it would be impossible to use the standard CZ ground relay. To meet this condition, a special ground relay was proposed to operate on the residual current of the three line-current transformers and whose voltage element would be connected in the delta of an auxiliary set of star-delta potential transformers; the timing element being inverted to shorten the time delay as the applied volt-

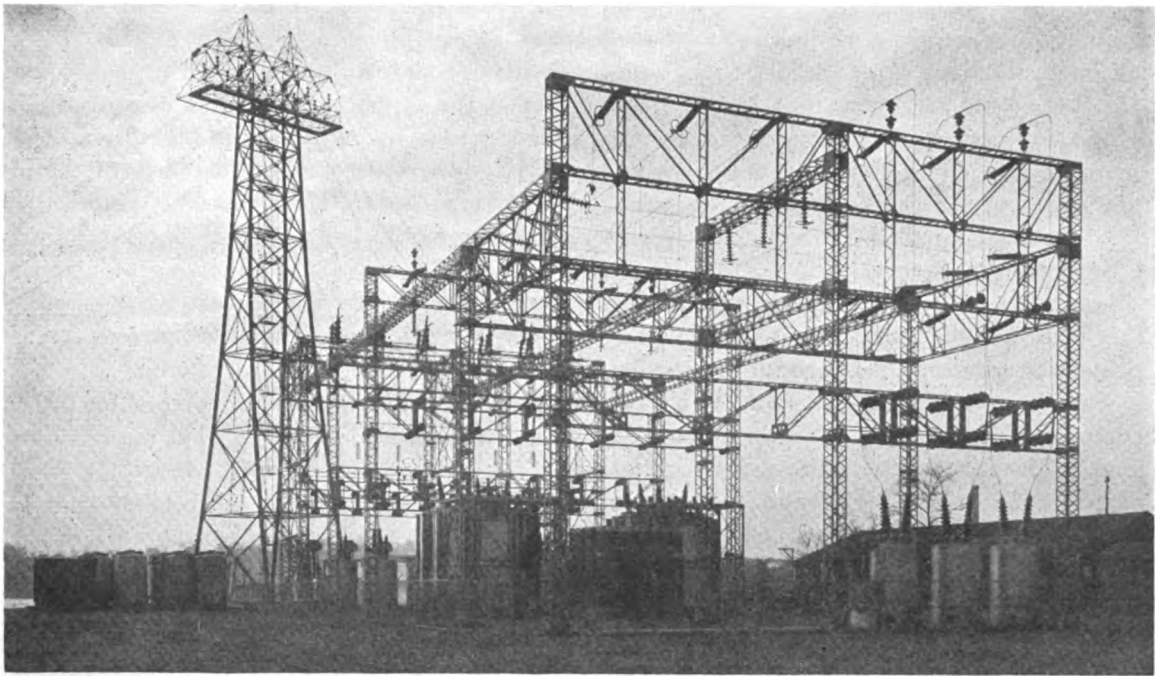

FIG. 4—110 KV SUBSTATION AND ONE TOWER ON THE WEYMOUTH-MEDWAY LINE

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age increased. One of the main disadvantages of the impedance relay scheme would be the cost of the high-tension potential transformers.

The method adopted is a modification of the third system, using cross-connected relays, Fig. 5, as a basis. Briefly the arrangement, with its advantages and disadvantages, is as follows:—

1—The balanced line relays *a* give instantaneous selective protection between lines or line sections operating in parallel. They are set for low current, and thus serve for ground protection as well as partial faults. Theoretically a fault very near a distant station would give equal currents in both lines, and thus would not cause sufficient unbalance to operate the relays; but this condition, while somewhat remote, is covered in item 2. In order to permit independent or single-line operation, the tripping circuit is opened by auxiliary switches of the tie and line circuit breakers respectively. The second line can be cut in for parallel operation without danger of tripping the running line, if the circuit breaker at the receiving end is closed first, since the directional elements of the line relays are open, thus breaking the trip circuit. As a matter of safety, however, the spring-return push buttons are held until the ammeters show that the incoming line is energized.

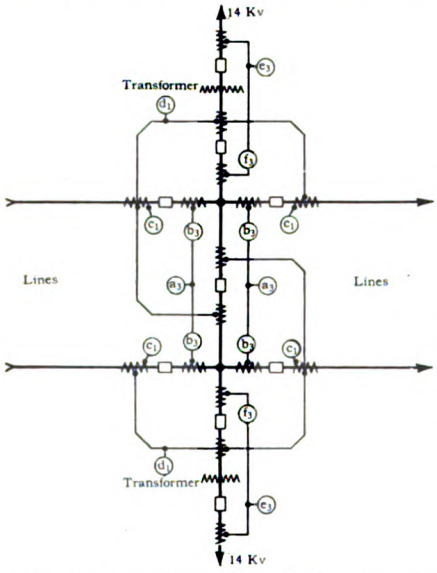
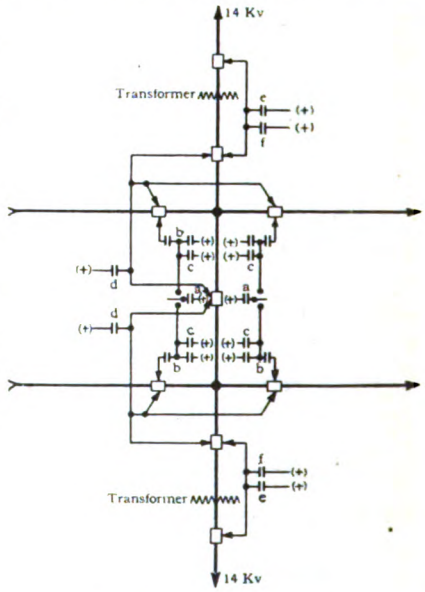



FIG. 5—(LEFT) EXAMPLE OF THE SECONDARY CURRENT CIRCUIT OF A 110 KV STATION

FIG. 5—(a)—(RIGHT) EXAMPLE OF THE DIRECT-CURRENT TRIPPING CIRCUIT OF A 110 KV STATION

RELAYS

a—Cross-connected, duo-directional, low-current, short time.
b—Line overcurrent, high current, selective time.
c—Line ground, low current, selective time.
d—Bus section ground differential, low current, short time.
e—Transformer differential, medium current, short time.
f—Transformer overcurrent, high current, long time.
Numerals show the number of relays.




2—The directional overload line relays *b* give successive timing protection for those sections not operating in parallel. These relays inherently give "back-up" protection for the preceding sections. They also give protection for sections operating in parallel, if the cross-connected relays should fail. If a fault should occur near a distant bus, it would be cleared, but both lines might come out. As for any directional relay schemes, however, the combination of circumstances necessary to produce this is improbable.

3—The selective timing ground relays *c* have all of the features mentioned in item 2 for giving protection and "back-up" protection for ground faults.

4—The bus section ground relays *d* are overlapping and give instantaneous protection for ground faults for the individual bus sections and circuit breakers. As only the residuals of the various sets of current transformers are differentially connected, the loop circuit normally has zero current and, therefore, the reliability, simplicity and safety are increased.

5—Each transformer has standard differential protection *e*, including the high and low-tension leads and oil circuit breakers.

6—The transformer overcurrent relays *f* give overload "back-up" protection for faults in the transformer leads, bus sections and lines on both the high and low-tension sides.

7—There is an apparent possibility of tripping more circuit breakers than are necessary during a fault, due to the interconnection of the directional contacts of the line relays, and due to the phase distortions resulting from the use of low-tension potential transformers; but a search of operating records available does not indicate that this condition has been experienced in practice. It should also be noticed that improper tripping would probably not occur even if the directional contacts of an outgoing relay were slow in opening, as the bus differential ground relay, or the cross-connected relays of the preceding line section, would clear the fault before the current elements would have time to operate. Further experience will indicate whether high-tension potential transformers are required.

8—The loadings on the current transformers were checked and found satisfactory.

The present installation of the 110 000 volt system is as shown in Fig. 1 (a) but the relay system has the basic elements described above.

*The Advantages* are, in general—the system is not affected by the presence or absence of back-feeds. Standard relays and schemes are used, although the combinations are somewhat new. Individual or parallel lines, as well as pilot wires, or other types of protection can be added. The installation is inexpensive and is easy to operate or maintain.

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# The Development of
# A New, High-Temperature Solder

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**Solder—to most of us—simply means the time-honored half and half. In many electrical applications, however, the temperatures are too high for our old friend. The solder described here is able to withstand these temperatures and yet dodges the evils which beset other "high temperature" solders.**

SOLDERS used for electrical apparatus generally consist of alloys of lead and tin, the most common having equal parts. Other common alloys consist of 58 percent lead, 42 percent tin; 67 percent lead, 33 percent tin; and 20 percent lead, 80 percent tin. These alloys start to melt at 183 degrees C., which means that a joint soldered with any of them will soften and may fail if heated to this temperature.

A solder having a higher melting point is very desirable for electrical joints, and pure tin, which has a melting point of 232 deg. C., has been used extensively. However, tin is expensive and the thermal advantage of tin over tin-lead solders (the ability to withstand high temperature) in electrical apparatus is not very marked. This will be shown by tests described later. Disadvantages of the use of pure tin as solder are the necessity of closely fitting the members to be joined, and of employing skilled operators.

Attempts have naturally been made to replace tin and tin-lead solders, but prior to the present developments, none has been successful on a practical scale. This is due to the rather severe requirements which must be met by a solder to be used in electrical apparatus. These requirements are:—

1—The solder must work satisfactorily with the non-corrosive soldering fluxes, employed in the soldering of electrical apparatus.

2—The solder should have a high melting point.

3—The solder should not contain any easily oxidizable metals.

4—The solder must have the physical properties required as to strength and ductility at the temperatures encountered under severe service conditions.

5—There should be no difficulty in obtaining a uniform composition of the solder in large scale manufacture.

6—The soldering operation should deviate as little as possible from common practice and should not require exceptional skill of the operators.

A solder which does not fill these requirements will not be successful in practical work and the failure of earlier experiments was due to the fact that one or several of these requirements were not met. Binary lead-cadmium alloys, for instance, oxidize too easily when molten to be of any practical value as solders. The oxidation can be suppressed by addition of tin or zinc. The addition of tin is undesirable, since tin with lead and cadmium forms a ternary alloy, melting at 145 degrees C., and a solder containing these three metals will therefore, be inferior to even the straight tin-lead solders. Addition of zinc has two disadvantages: —The solder cannot be used with the non-corrosive fluxes which are necessary in the soldering of electrical apparatus, and it is questionable whether the alloy will remain stable under service conditions. Experience and investigations conducted on the behavior of fusible boiler plugs have shown that alloys of lead and tin, where zinc had been added merely to cheapen the alloy, disintegrated in the course of time.

Alloys containing zinc as a main element are out of question because of the two reasons mentioned above and also because these alloys are brittle. The requirement as to ductility is rather severe for a solder to be used in railway motors. Binary lead-antimony or tin-antimony alloys, containing antimony in excess of approximately two percent cannot be used as solders, since it has been found that these solders under vibration exhibit intercrystalline failure.

### PRESENT INVESTIGATION

IT WAS evident at the beginning of the present investigation that only lead or certain lead-basic alloys would possibly satisfy all the requirements mentioned above. Although lead does not alloy with copper as easily as tin does, it can nevertheless be used as a solder. Addition to lead of other metals which alloy more readily, as for instance tin and silver, must result in making the soldering process easier. Tin can, however, be added only to a limited amount, since otherwise the melting point of the alloy will be depressed to that of the common lead-tin solders. Based on theoretical considerations the solders to be tested were limited to the following: Lead; an alloy of 3.5 percent tin and the remainder lead; an alloy of 2.5 percent silver, 0.25 percent copper and the remainder lead. The reasons for selecting these particular compositions are given later.

To solder with lead proved to be a difficult operation. Since lead has a comparatively high melting point —327 degrees C.—a hot iron is necessary for soldering. Having the iron too hot results, however, in carbonization of the rosin contained in the flux, which keeps the the solder from adhering to the metals to be

*Dr. Silberstein was in the Materials and Process Engineering Dept., Westinghouse Electric & Mfg. Co. when this solder was developed.

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joined. The difficulties encountered in soldering with pure lead were sufficient to eliminate it. The working qualities of the lead-tin and the lead-silver-copper alloys were found to be much better than those of pure lead, the last mentioned alloy being the best one.

In soldering practice it is essential that the solder be fluid enough to fill the space between the members to be joined without, however, running through this space. The solder should, therefore, when solidifying pass through a stage of gradually decreasing fluidity. This takes place in alloys which have a melting range marked by an upper melting temperature, above which all metal is liquid, and a lower solidification temperature below which all metal is solid. Within the melting range part of the metal is molten and part is solid, the amount of each depending upon the temperature, so that the alloy on solidification is getting more and more viscous and pasty until finally it is all solid. Pure metals and eutectic alloys are characterized by sharp melting points, i.e., they are either entirely liquid or entirely solid and since they do not pass through a stage of decreasing fluidity, they have a tendency to run through joints, when used as solders. This is the reason for the difficulty in soldering with pure tin, which results in the necessity of fitting connectors

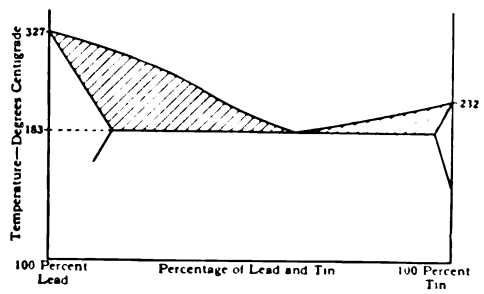


FIG. 1—AN EQUILIBRIUM DIAGRAM OF LEAD-TIN ALLOYS

At temperatures below the shaded portion the alloys are solid; in the shaded area the alloys are partly fluid; and above the shaded area are entirely fluid.

closely and the employment of specially trained men for soldering with this metal.

Lead and silver form an eutectic alloy at a content of 2.5 percent silver. This alloy has a melting point of 304 degrees C. An addition of copper was made to this alloy in order to make it pass through a viscous range on solidifying. The same effect could have been obtained by changing the silver content, but copper was chosen because its effect is much greater and because it adds to the strength of the alloy. An amount of 0.25 percent copper was thought sufficient for good working properties of the solder without introducing an element of hazard, and subsequent practical experience on large scale operation has established this.

It would be expected that soldering becomes more difficult the higher the working temperature of the solder. Since the lead-silver-copper alloy melts at a higher temperature than does tin, it should be more difficult to use, but practical experience shows that it is not. In fact, men who had previously used only ordinary tin-lead solders, state that they prefer the new alloy to pure tin solder. Tests have, of course, also been performed with other lead-silver-copper alloys. It might have been expected, that a greater copper content would result in better working qualities of the solder, since the variation in viscocity on solidifying would be more marked. However, all changes of composition brought reports of trouble in soldering. The first composition was found to be the best one and it was really surprising to note that such a small variation in composition as one-quarter of one percent was of decided influence on the soldering qualities. Operation on a commercial scale has shown that it is not difficult to keep the composition of the solder within these limits.

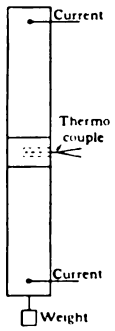


FIG. 2—AN ARRANGEMENT TO DETERMINE THE TEMPERATURE NECESSARY TO PRODUCE FAILURE OF A LOADED SOLDERED JOINT

## STRENGTH OF SOLDERED JOINTS AT HIGH TEMPERATURES

As shown in Fig. 1, only pure lead, pure tin and the eutectic alloy, containing 62 percent tin and 38 percent lead, have definite melting points. All other alloys melt within a range of temperatures, shown by the shadowed area. Practically all commonly used tin-lead solders start to melt at 183 deg. C. The belief sometimes found among electrical engineers, that joints soldered with an 80 percent tin, 20 percent lead or 90 percent tin, 10 percent lead alloy will withstand higher temperatures than joints soldered with the ordinary half and half solder is entirely unfounded.

TABLE I—TEMPERATURE TEST OF VARIOUS SOLDERS

| Solder | Temperature at which Failure Occurred Deg. C. |
|---|---|
| 42/58 tin-lead | 175 to 179 |
| Pure tin | 210 to 214 |
| 3.5/96.5 tin-lead | 230 to 239 |
| Pure lead | 314 to 317 |
| 2.5/0.25/97.25 | 296 to 301 |

An alloy containing 3.5 percent tin and 96.5 percent lead should, according to the equilibrium diagram, start to melt at about 280 degrees C. However, alloys as cast—and the solder in a joint is but a casting—are rarely in equilibrium. It is therefore, to be expected that this alloy starts to melt at a lower temperature. Ordinary methods to determine this point would have little practical value in this case. Since soldered joints often are subjected to stresses, it was decided to heat a joint of certain area and held under a certain load until it failed.

Two copper straps, ⅛ in. × 1 in. × 10 in. were soldered together, overlapped, the soldered area being 1 in. × 1 in. as shown in Fig. 2. A hole 1/16 in. in

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diameter and ¾ in. deep was drilled in the upper strap and a thermocouple placed in the hole. A weight of 50 lbs. was attached to the lower strap and electric current passed through the straps until the joint failed. Several tests were made using this method, the results being given in Table I. These tests show that, eliminating lead, which is undesirable from a practical point

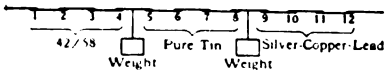


FIG. 3—AN ARRANGEMENT TO DETERMINE FAILURE TEMPERATURE OF JOINT MADE WITH DIFFERENT SOLDERS

of view, the lead-silver-copper alloy stands the highest temperature under stress.

The tests with this alloy were repeated, using tinned-copper straps as members. In most cases in practice copper members are tinned previous to soldering and it might be expected that presence of tin in the lead-silver-copper alloy might lower its resistance to high temperature similar to its action in pure lead. This was, however, not found to be the fact. The joints all failed at temperatures between 295 and 300 degrees C. The reason for this is the following: Tin,

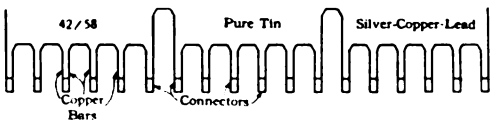


FIG. 4—AN ARRANGEMENT TO DETERMINE THE EFFECT OF DIFFERENT SOLDERS ON JOINT RESISTANCE

contained in tinned copper is partly combined with copper to a metallic compound of the formula $Cu_3Sn$* which has a melting point of over 700 deg. C., and only part of the tin is free and has a melting point of 232 deg. C. On soldering with the new alloy, this free tin reacts with the silver and the copper of the solder forming the high melting point compounds $Ag_3Sn$ and $Cu_3Sn$. Only if more tin is present than is necessary to form these compounds, can it lower the ability of the solder to stand elevated temperature under stress. However, such amounts of free tin on tinned copper straps, connectors and other copper parts are never present under practical conditions. Even if such amounts of excess tin were present, the members to be soldered would be rejected as unfit. This has been established by a number of tests, similar to those mentioned, but where straps and connectors of different shapes and sizes were used as members.

Another test which showed the relative value of solders in withstanding high temperature under stress was the following: Copper straps, 1/16 in. × 1 in. × 5 in., were soldered with the following three kinds of solder: 42/58 tin-lead alloy, pure tin and the new silver-lead-copper alloy. Four lap joints were made with each kind of solder, the soldered section being 1 in. × 1 in. in all cases as in Fig. 3. Electric current was passed through the straps, which were under tension

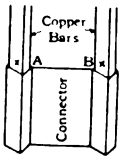


FIG. 5—AN ENLARGED SKETCH OF A SINGLE CONNECTOR AND TWO COPPER BARS USED IN FIG. 4

until the joints failed. When one joint had failed, contact was made at this place by brass clamps, and the test continued.

Considering that the 42/58 tin-lead alloy has the lowest melting point, failure would be expected first on all joints soldered with this alloy. However, one joint marked superiority of the tin-soldered joints could be soldered joint failed next, then a joint soldered with the 42/58 alloy, then a tin-soldered joint and so on.

TABLE II—SOLDER CHARACTERISTICS

| | Conductivity Percent (Copper, 100 Percent) | Temperature Coefficient |
|---|---|---|
| 42/58 tin-lead alloy | 10.1 | 0.00402 |
| Pure tin | 12.1 | 0.00419 |
| Silver-lead-copper alloy | 8.2 | 0.00379 |

This test was first conducted with a series of bare strips, and then repeated with a series of insulated strips. In both cases the results were the same, namely that the joints soldered with the 42/58 alloy and tin-soldered joints failed at the same current, and no marked superiority of the tin-soldered joints could be found.

The joints soldered with the silver-lead-copper alloy failed at much higher current. The failure of the tin-soldered joints and the joints soldered with the 42/58 alloy at the same current can be explained in the following way: As has been mentioned previously, soldering with tin is more difficult than soldering with half and half or 42/58 tin-lead alloy. As a result, joints, soldered with half and half or 42/58 tin-lead alloy are generally better than if soldered with tin. This in turn means, that the former joints are heated to lower temperatures than are the latter at a given current or in other words, the apparent advantage of the higher melting point of pure tin is off-set by its disadvantageous working properties.

TABLE III—CONTACT VOLTAGE DROP OF JOINTS MADE WITH DIFFERENT SOLDERS

| Amperes | 42/58 Tin-Lead Alloy Millivolt Drop | | | Pure Tin Solder Millivolt Drop | | | Silver-Lead Alloy Millivolt Drop | | |
|---|---|---|---|---|---|---|---|---|---|
| | Maximun | Average | Minimum | Maximum | Average | Minimum | Maximum | Average | Minimum |
| 200 | 2.0 | 1.9 | 1.7 | 2.0 | 1.9 | 1.7 | 2.6 | 1.9 | 1.8 |
| 300 | 3.2 | 2.8 | 2.4 | 3.2 | 2.7 | 2.5 | 3.2 | 2.8 | 1.8 |
| 400 | 4.4 | 4.1 | 3.8 | 4.2 | 4.1 | 3.8 | 4.6 | 4.2 | 3.9 |

## CONDUCTIVITY OF SOLDERS AND SOLDERED JOINTS

THE ELECTRIC conductivities and temperature coefficients of various solders are given in Table II. To determine the influence of the solder on the con-

*Cu is the chemical symbol for copper, *Sn* for tin and *Ag* for silver.

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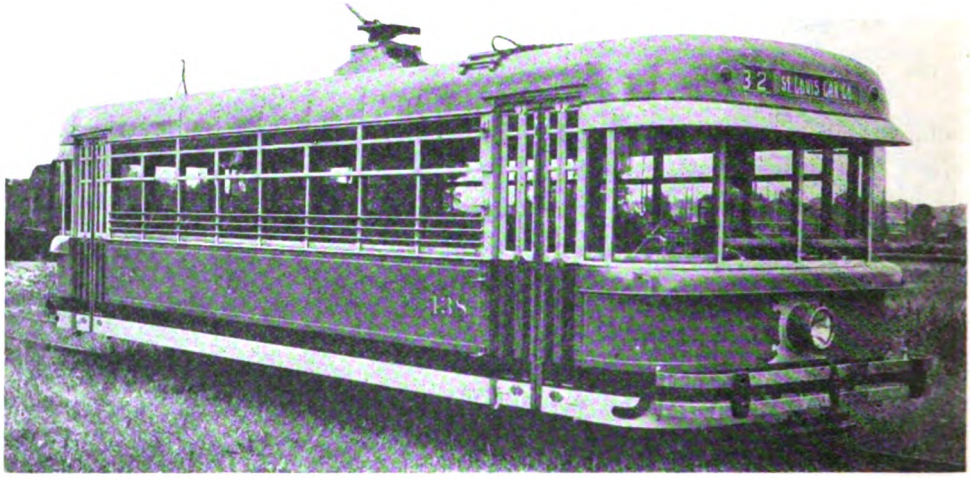
ductivity of soldered joints, the following tests were made. Copper straps, ¼ in. × ¼ in. were soldered into connectors using the three kinds of solder mentioned in Table II. Eighteen connectors were soldered as shown in Fig. 4, the first six using 42/58 tin-lead alloy, the next six using pure tin solder, and the last six using the silver-lead copper alloy. Current was passed through the joints, starting with 200 amperes. The millivolt drops across the connectors as shown at *AB*, Fig. 5, were determined after 10, 20, 30, and 40 minutes intervals. The current was then increased to 300 amperes and the same millivolt readings taken. This was repeated again after the current had been increased to 400 amperes. The maximum, minimum and average values of the millivolt drop are given in Table III. Since six joints were soldered with each kind of solder and four readings taken for each current, there were altogether 24 readings taken for each current. It was found during the testing that the exact location of the points *A* and *B* across which the drop was determined had quite an influence on the readings. This, in conjunction with the fact that there is practically no difference between the average resistance of joints soldered with the different kinds of solder, indicates that the resistance of the solder in a joint is small in comparison with the total resistance of the joint and that the resistance consists essentially of the resistance of the copper.

The use of the silver-lead-copper alloy is to be recommended for electrical apparatus where the common soft solders are apt to fail on account of too high temperatures being encountered in service. Service results of railway and mine motors where the new solder has replaced the old ones have been very satisfactory and the soldering trouble previously experienced has been eliminated. The first place where the new solder was applied on a practical scale, was in the motors of the electric locomotives of the Virginian Railroad, which are the largest and most powerful in the world. Later the solder was used in other railway motors and mine motors, where trouble with the old solders had been encountered. The results have in all cases been very satisfactory.

# The New Birney Car

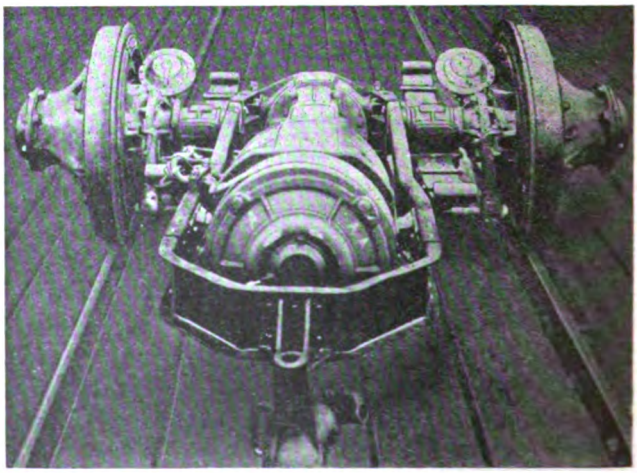
THE "New Birney" one-man car has a host of notable features. An ability to accelerate from standstill to 20 miles per hour in five seconds—double that ordinarily obtained; live rubber separating the steel flanges from the core of the wheels to absorb vibration and reduce noise; rubber insulation at the points of contact between car body and and driving units; drive carried from the motor through a propeller shaft, universal joint and differential to each pair of wheels; and a weight of about half that of the ordinary street car—these are some of the outstanding features.



**The New Streamline Birney Car Built for City Service Weighs but 18 000 Pounds and Seats 39 Passengers**

Two 50 hp motors are used, one on each of the two, two-wheel trucks. The wheel and axle arrangement is similiar to that of an automobile. The wheels may turn relative to the axle, and to each other thus eliminating screeching on sharp turns. Each wheel has a practically noiseless, metal to metal, internal expanding brake in place of the usual shoe.

Many other features add to the car's attractiveness and riding qualities. Nothing except the wheels and wheel cradles are visible below the car body. The car steps are but 13 inches from the street level. All glass is shatter proof and the windows are weather stripped. The seats are spring mounted and are upholstered in leather. All wiring and control equipment is carefully concealed, only one or two control handles being visible at the front. The car has complete safety equipment. The motorman must have either his hand or his foot on controls while the car is in motion or it is automatically stopped.



**One of the Two Differential-Drive Trucks**

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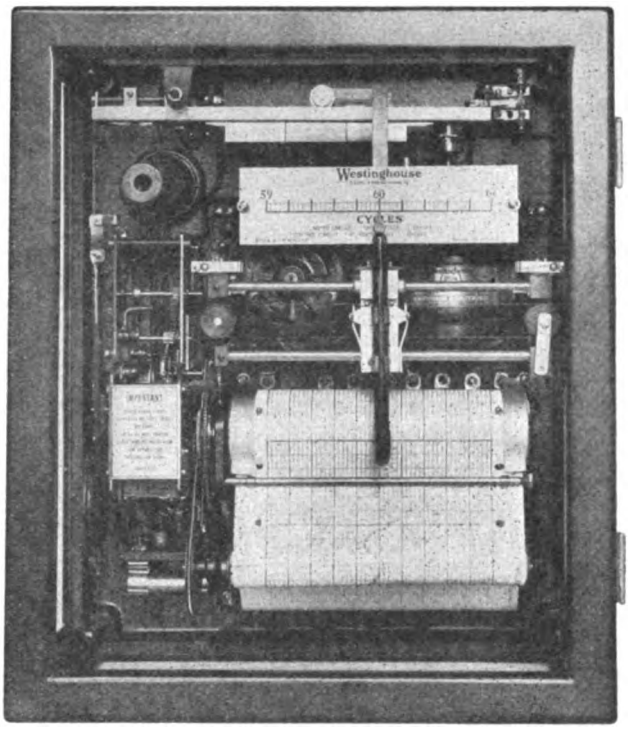
# The Centrifugal Frequency Recorder

F. S. STICKNEY
Meter Engineer,
Westinghouse Electric & Mfg. Company




**Frequency, or speed of rotation, is one of the most difficult of the common quantities to measure by precision methods. Where the frequency is constant, the method of counting cycles for an accurately measured period of time is satisfactory. But most alternating-current systems are subject to instantaneous variations in frequency which are not recognized by this method of integrating cycles. The method is therefore limited in its use to the measurement of average frequency only. Frequency measuring devices of the instantaneous type have always been in demand, but since the advent of interconnected alternating-current systems a far greater degree of precision has been required in these devices than in other commercial indicating and recording instruments. For instance, the accuracy of a good portable wattmeter is about one-fourth of one percent of full scale, while good frequency control involves a study of variations of the order of one hundredth of a cycle.**

LARGE alternating-current systems are able to maintain their frequency so nearly constant that a frequency meter of extraordinary sensitivity is needed to show normal variations accurately. It is also essential that all of these variations in frequency be recorded, even those of very short duration. Average frequency is readily observed and kept under control by means of the synchronous motor clock, but instantaneous frequency, with its associated problem of load distribution, is still a difficult factor to control. With each generating station equipped with a sensitive and precisely accurate frequency recorder, the problem of satisfactory load distribution can be greatly simplified.

The centrifugal frequency recorder has been recently developed to meet this need for an extremely sensitive means of recording instantaneous system frequency. With it, instantaneous frequency variations of one percent of one cycle in a 60-cycle circuit are readily recorded. This result has been accomplished by application of the principle used in flyball governors for steam turbines and other prime movers, i.e., the centrifugal force produced by a mass rotating at high speed is enormous in proportion to the weight of the mass itself. Adaptation of this principle results in a recording instrument with extremely high operating forces, permitting the use of heavier and stronger parts, thus making the instrument more sensitive and less delicate.

When a mass is being rotated at high speed around an axis, the centrifugal forces developed by it are proportional to the square of the speed of rotation. If the mass is rotated by a synchronous motor, centrifugal force will be proportional to the square of the frequency of the circuit which supplies the motor. Any change in the frequency of the circuit will produce a change in centrifugal force proportional to the difference of the square of the frequencies before and after the change. Application of this fundamental principle produces a frequency recorder of great sensitivity, since large variations in operating force are produced by small variations in system frequency.

The complete operating principle of the new recorder is explained with reference to Fig. 1. A self-starting synchronous motor *A*, running at relatively high speed, drives a directly connected centrifugal device *B* which transfers centrifugal force into an axial thrust upon a vertical push rod *C*. This axial thrust is proportional to the square of the frequency. A traveler arm *D* is pivoted at one end *J*, the other end being supported by push rod *C*. The contacts *E* are used to control a reversible motor *F*, which operates a sliding pen carriage assembly *G*. This assembly carries a rigid vertical arm *H*, which draws traveler *I* along traveler arm *D* as the pen is moved.

As long as the frequency remains constant, the whole system of weights remains in equilibrium, and the contacts remain open. Taking moments about the pivot *J*, the unbalanced weight of traveler arm *D* plus the weight of traveler *I* produces a moment equal and opposite to the moment of the upward force from push rod *C*. This condition of equilibrium lasts as long as the centrifugal force remains constant.

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Any increase in frequency increases the speed of the synchronous motor, increases the centrifugal force produced by the flyballs *K*, increases the upward thrust on push rod *C*, and throws the system out of equilibrium, thereby closing the upper pair of contacts. This starts the control motor in a positive direction, moving

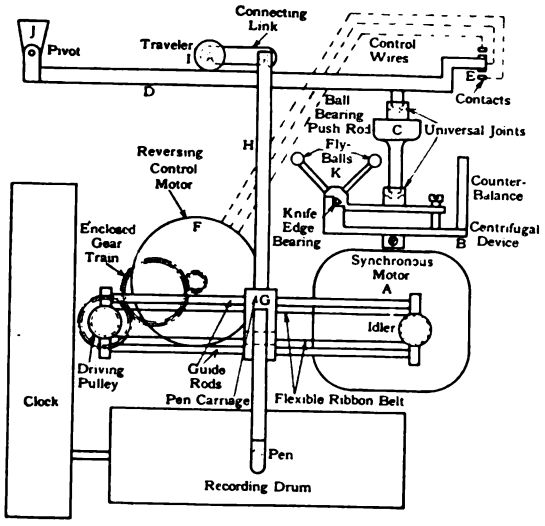


FIG. 1—SCHEMATIC DIAGRAM OF THE CENTRIFUGAL FREQUENCY RECORDER

the pen carriage assembly to the right. As the assembly moves, the traveler *I* is carried along the traveler arm, thereby increasing its moment about the pivot *J* and tending to restore the system to equilibrium. When this is accomplished, the upper contacts open and the control motor stops, leaving the recording pen in a new position further up scale, indicating an increase in frequency. When the frequency decreases the lower contact is closed, the motor starts in a negative direction, the pen moves to the left, restoring equilibrium and opening the contacts, the pen indicating the reduced frequency.

In operation, any small change in system frequency immediately acts to throw the mechanical system of the recorder out of equilibrium, producing motion of the recording pen within a small fraction of a second. The device is therefore, instantaneous in the ordinary sense that it is not limited to definite intervals of time be-

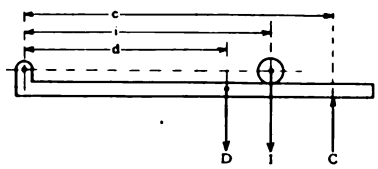


FIG. 2—MOMENT DIAGRAM OF THE CENTRIFUGAL FREQUENCY RECORDER

tween readings. There is a slight, continuous lag between actual frequency and the position of the pen, but this lag is always present in any indicating or recording instrument having a low natural period of oscillation. The speed of the centrifugal frequency recorder compares favorably with that of other curve-drawing, electrical-recording instruments of the instantaneous type.

Several interesting problems in kinetics were encountered in designing the moving parts of the recorder. Whenever the traveler *I* is moved horizontally along the traveler arm, an opposite horizontal reaction due to friction appears in the traveler arm. This force might have been sufficient to produce perpetual instability of the whole moving system, causing it to hunt continually, but such a difficulty was avoided by placing pivot *J* and the center of traveler *I* on the same horizontal axis, thereby reducing the moment of all undesirable reactions to zero.

In the centrifugal device it was found desirable to use two flyballs correctly proportioned to make the axial force on the push rod independent of the angular position of the flywheel assembly. This eliminates errors which might arise from adjustment of contacts or of length of push rod.

Calibration of the instrument depends upon the relation of three quantities. Centrifugal force is the

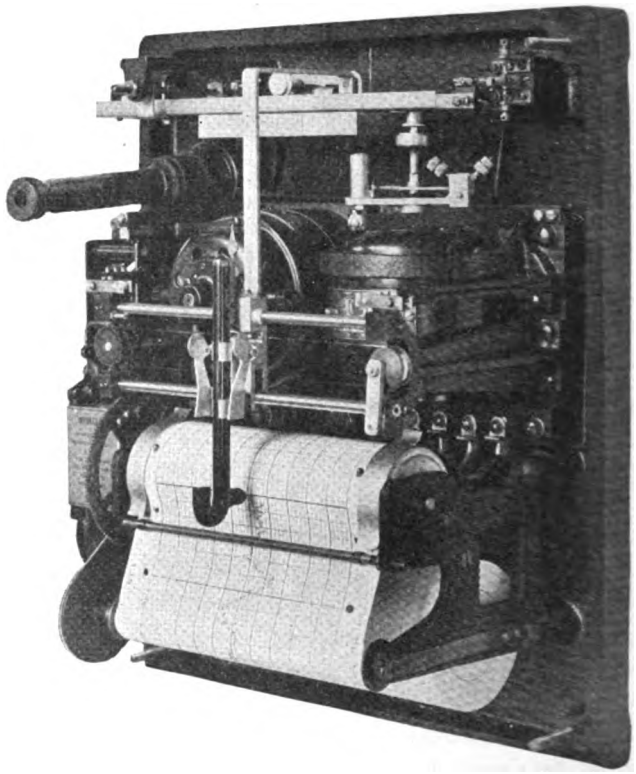

FIG. 3—THE CENTRIFUGAL FREQUENCY RECORDER WITH COVER REMOVED

quantity being measured, and it is first resolved into an upward force in the push rod. Referring to Fig. 2:—

$Dd$ = Moment of unbalanced dead weight.
$Ii$ = Moment of moving weight.
$Cc$ = Moment of thrust in push rod.

Taking moments about the pivot:—

$$Dd + Ii = Cc$$

In operation, $Dd$, $I$ and $c$ are constant, $C$ represents frequency and $i$ represents the position of the pointer. In calibration $I$ and $d$ are used as variables to bring about the desired relation between $C$ and $i$. Calibrating adjustments are made by changing the position of dead weights to vary the unbalanced moment of these weights with reference to the pivot, and by changing the effective value of the traveler weight $I$. These adjustments are made with micrometer screws.

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When flyballs, dead weights and moving weights have all been adjusted to correct ratio, the calibration of the recorder has been permanently determined. During the calibration process, changes in the amount of unbalanced moment of the traveler arm result mainly in moving the visible range of the instrument up and down the scale of frequency, while changes in the moment produced by the traveler weight result mainly in widening or narrowing the visible scale range. For instance the mid-point of the scale may be moved from 50 to 60 cycles by adding dead weight to the traveler arm, while the range of the instrument may be changed from 59-61 to 58-62 cycles by adding weight to the moving traveler. Changes in the mass of the flyballs affect both mid-point and width of the visible scale. The different ranges required commercially are obtained by using various combinations of flyballs, moving weights, and dead weights.

When the fundamental calibration of the instrument has once been determined, only a severely damaging shock or intentional adjustment can change it. For subsequent checking, a check of the rated frequency point of the scale is usually sufficient. Other points ordinarily remain correct unless the ratio or position of weights is altered by outside means.

The centrifugal frequency recorder is inherently free from the errors usually found in frequency indicators and recorders. As long as the synchronous motor remains in step, there can obviously be no possibility of error from voltage or wave-form. Some of the older types of frequency meters are based upon the impedance bridge. Such instruments nearly always have a temperature coefficient resulting from the use of condensers or reactors. These temperature errors are not serious for ordinary measurements of frequency but, where extreme accuracy is required, they may become appreciable. The centrifugal frequency recorder is inherently free from temperature error. The only possibility of such error lies in the coefficient of linear expansion of the metals used in the centrifugal device. Since all these details are small and of rigid construction, there is practically no change due to temperature. This is confirmed by tests which show no appreciable errors from self-heating or from ordinary changes in ambient temperature.

Since, in frequency measurements, only a narrow range close to system frequency is of interest, frequency recorders are ordinarily provided with suppressed zero scales. The centrifugal-type recorder, with a visible scale 5.25 inches in length, covering the range between 59 and 61 cycles, has a full scale length of 81.39 inches from 0 to 61 cycles. It is obvious that an instrument with a square-law scale nearly seven feet long can be read with a high degree of accuracy near its upper end. Preliminary experiments have shown that it is entirely possible to build a 60 cycle centrifugal frequency recorder with a full scale range of but one cycle, which, if the visible scale is 59.5 — 60.5 cycles amounts to 5.25 inches per cycle. Such sensitivity, while possible, is at the present time in advance of developments in frequency controlling devices. Today, in a commercial 60 cycle system of average size, continuous frequency variations amounting to one-tenth of a cycle above and below rated frequency are usual. This results in a present demand for frequency recorders with ranges of the order of 59-61 or 58-62 cycles, giving a working sensitivity of about one or two hundredths of a cycle. However, with future improvements in governing devices, and with growth in the size of interconnected systems, the industry will probably soon be able to make use of the greatest sensitivity possible in this type of frequency recorder.

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# Armature Coils Used to Maintain Railway Motors*

A. C. ROE

### ASSEMBLING OPERATIONS

The assembling operations for different kinds of coils vary so that no general rule can be given. There is, however, one operation common to all, that of cleaning and tinning the coil leads. This is done before the coils are pressed to prevent the wires from being displaced in handling. A modern well ventilated tinning department is shown in Fig. 17.

The first operation for coils types *D*, *E*, and *M*, when they are wound in paper cells, is to assemble together the number of single coils that make up a complete coil. Glue is placed in the slot section between coils, the sides squared up and the coils tied at all four corners. Coils wound complete, as types, *F*, *G*, *N*, *P*, and *S*, or coils wound single without cells must have the slot sections stiffened and means provided to hold the coil rigid. One method consists of using a combination slot wrapper built up of fishpaper with treated cloth cemented to the center portion. This wrapper is started between the assembled coils, which have been dipped in varnish, and wrapped around the coil semi-tightly. Another method employes shallacked strips, i.e., strips of fullerboard or fishpaper coated on both sides with a special shellac. These strips are placed depthwise in coils of types *D*, *E*, *F*, *G*, *M*, and *N* and widthwise in coils of types *G*, *P*, and *S*. In Fig. 18, the shallac strips are shown being inserted.

*Continued from the JOURNAL for October, p. 489.

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The assembling operations for type *S* coils consist of taping each individual lead, taping the group of leads together, inserting the shellac strips and tying the coils for pressing.

For strap copper coils, types *H* and *K*, the assembly operations consist of applying insulating material to each single coil or bare strap. These can be divided into six methods; in the first, all the straps or single coils are taped on the ends and through the slot sections; in the second, only the ends of all straps are taped; in the third, only the odd numbered straps, as 1-3-5 etc. are taped on the ends; in the fourth, only the even numbered straps as 2, 4, 6, etc. are taped on the ends; in the fifth, the old numbered straps are taped all around; and in the sixth, the even numbered straps are taped all around. With methods 2, 3 and 4, the tape is extended ¾ to one inch into the slot section. With methods 3, 4, 5 and 6, the untaped straps are reinforced at the ends with a few turns of tape, and at the leads a mica splitting is placed under the tape. This adds protection where the heat from soldering is greatest. When methods 2, 3, and 4 are used, the

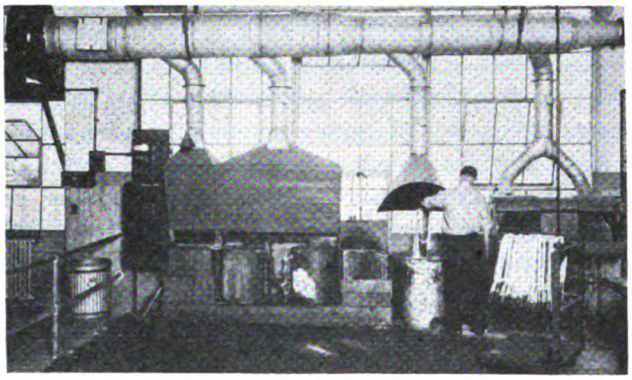

FIG. 17—A MODERN TINNING DEPARTMENT

wrapper is interwoven between the straps in the slot section and the tape extending under the wrapper breaks the joint between wrapper and tape.

Methods 4 and 6 result in a thin, compact coil, as compared to methods 3 and 4, but require more care in winding the armature, as there is more chance of damage to the final layer of tape.

Cotton or treated-cloth tape may be used for class *A* coils, or mica tape for class *B* coils. The tape may be applied by hand, or by machine, as shown in Fig. 19.

The type *P* coil requires bending the top leads as shown in Fig. 20, which brings them out on top of the coil and free to pass the adjacent coil.

### PRESSING OPERATIONS

The pressing operations can be covered under two headings, hot and cold pressing. In hot pressing, pressure is applied by means of heated plates. The methods and tools generally used apply pressure to only two sides of the coil, the pressure being controlled by the operator. This method is the one commonly used for coils types *D*, *E*, and *M*, and for coils types *F*, *N*, and *P* when the wrapper is interwoven.

The cold-pressing method shown in Fig. 21 is more modern. Shellac strips are used. The coils are placed in an automatically controlled electric oven to soften

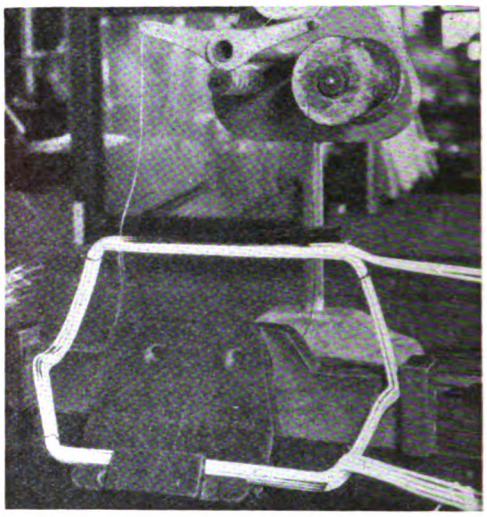

FIG. 18—SHELLACKED STRIPS BEING INSERTED WIDTHWISE IN A COIL TO PROVIDE STIFFENING

the shellac, then into an individual iron press, where pressure is exerted on all four sides. The pressing jaws are machined to receive the coil sides, and this controls the pressure, as the limit is reached when both members of the press meet. By this method both temperature and pressure are controlled.

Cold pressing insures a smooth, even slot section and allows the slot wrapper to be applied free from wrinkles or soft spots whereas, when the wrapper is applied to a loose coil and then pressed, the pressure is applied through the insulating material, forcing it into the space between the wires. Thus maximum protection to ground is not secured as these strains impair the dielectric strength of the insulating material.

FIG. 19—TAPING A COIL WITH A TAPING MACHINE
The platform supports the coil, freeing the operator's hand for tightening the mica tape.

### FIRST VARNISH TREATMENT

Dipping and baking the coils in a high grade varnish follows the pressing operation. The coils should remain under varnish until all air is replaced by the

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varnish, which is indicated when bubbling ceases. The varnish should be kept clean and at the correct specific gravity. Correct tanks and a filtering press as shown in Fig. 22 will help accomplish this.

INSULATING

The finishing tape is applied either by taping machines or by hand, using a tape holder or reel. The type of coil determines the method used and also the

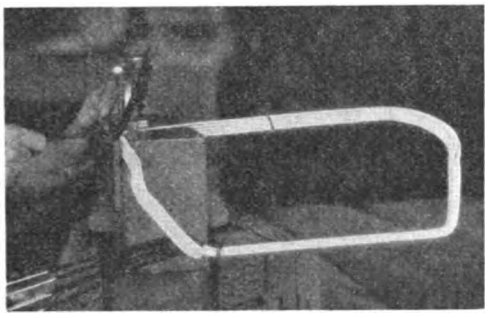

FIG. 20—BENDING THE TOP LEADS OF A TYPE *P* COIL

manner of holding or supporting the coil. Coils of type *D, E, F, G, M, N,* or *P* can be taped or wrapped by machine. Paddled arm rests and special pounding blocks are essential.

The double-loop type *S* coils are hand wrapped due to the size, type and method of bringing out the leads. Fig. 23 shows the method of holding the coil.

The strap copper coils, types *H* and *K,* are hand wrapped. They require a special fixture that can be adjusted to various positions, to hold the coil securely, by supporting it at two points.

There are four standard terms used to indicate the method of applying tape*; half lapped, spaced, butted and edged lapped. Of these, half lapping is used the most. It consists of applying each succeeding turn of tape so that the left-hand edge divides the preceding

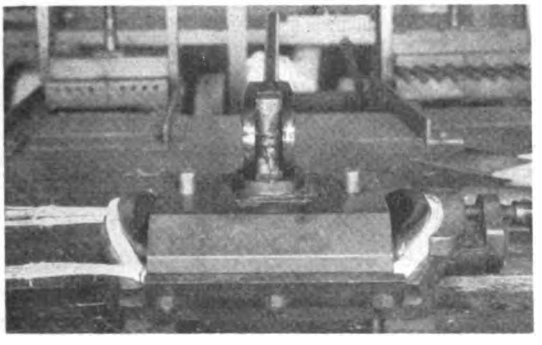

FIG. 21—COLD PRESSING A COIL

turn in half, resulting in two thicknesses of material. Half overlapped tape provides a good seal against the entrance of dirt or moisture, etc. Spaced taping consists in leaving a space of 1/16 to ¼ inch or more between the edges of each consecutive turn of tape. This applies one thickness of material and is used principally as a binding medium, for holding wires together etc. However, when the thick tape is used, such as asbestos and where it does not permit overlapping, spaced taping is necessary. Butted taping consists of laying the edges of the tape close together. When the coil must be sealed and the finishing tape is used as a binding, edge lapping is used. This consists of slightly overlapping the edges of the tape.

The insulating materials commonly used in armature coils are;—paper as a stiffening medium; cotton as a covering on copper wire, woven into a tube and called sleeving; tape in various grades, widths and thicknesses, made into cambric and treated with varnish, the resulting product being treated cloth in sheet or tape forms; asbestos with different mixtures and percentages of organic material in sheet, tape or sleeving form; mica combined with paper in sheet or tape form (in some cases pure mica splittings are used or held together with various types of bonds, forming sheet mica, cold or forming grades); varnish, baking and air drying, applied by dipping and brushing or spraying; compounds or gum applied by the vacuum and

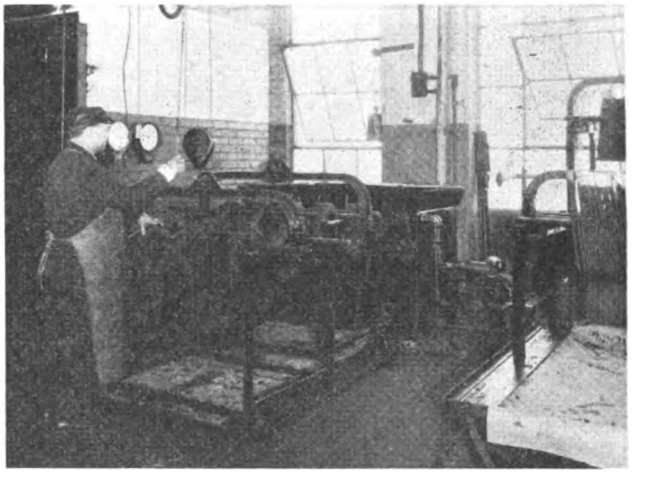

FIG. 22—THE INTERIOR OF A WELL EQUIPPED COIL DIPPING AND BAKING DEPARTMENT

air-pressure. Thus there are only a few basic materials but legions of grades, makes, sizes and sources of supply which should be carefully considered if best results are to be obtained.

The various steps of coil construction have been discussed but no mention has been made of the most vital item—inspection—which begins with checking the materials as to proper grades, or sizes, and is part of each step—as checking dimensions of the coils, testing for defects after each operation, weeding out poor workmanship, checking coils to predetermined standards, testing for short-circuits, crossed wires, etc.

ARMATURE COIL EVOLUTION

The early armatures were all hand wound, the wire being wound directly on the core. This method retarded development and resulted in the trial of a unit or coil wound to a predetermined shape and then applied to the core. This first coil was of the elliptical or *D* type and proved satisfactory for a while. As this winding required a large number of deep and narrow slots, an attempt was made to use a larger number of

*See the JOURNAL for July, 1928, p. 365.

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single coils per slot, but the elliptical-shaped end windings defeated this step as the ends were difficult to shape and place.

This led to the development of the two-layer type of end winding, using a diamond-shape, mould-wound (single) coil. The end windings projected straight out and necessitated retaining or end bands. This method allowed the use of one to five single coils per slot. Then, to reduce the overall length of the armature, the short-type coil was developed. This gave a stiffer end winding, and allowed the use of one to five single coils per slot, but still required end bands.

The coils up to this time were all mould wound, either single or complete, the latter type having the advantage of more uniform arrangement of the wires at the radius or corners*, open construction, which

FIG. 23—HAND WRAPPING A TYPE *S* COIL

The special jaws of the vise are smooth. Handling the roll of tape is facilitated by the use of a convenient holder. Spring clips hold the wrapper in place until secured with tape.

permits better varnish penetration, and the use of controlled pressure applying methods.

The short-type coil requires less coil end extension parallel to the shaft than the diamond type, but the short-type coil ends require greater depth on a radius than the diamond. Therefore, one type could not be used to the exclusion of the other. During this period only round wire was used for mould wound coils, strap copper being used for the larger capacity motors.

Several attempts were made to develop a coil having short and shallow end windings, or a combination of the short and diamond types. The final results were the drop-type coil, in which the diamond loop had been changed to a shallow involute drop. This meant a saving in weight and also allowed the use of from one to six single coils per slot.

During this stage of development, there were other points under consideration, foremost of which was the necessity of improving the space factor, or placing more copper in the same space. Square or ribbon wire were tried. However, the short or diamond-types of mould-wound coils were not adaptable to the use of square or ribbon wire. Round and square wire and some sizes of ribbon can be wound on the drop-type moulds. This led to the tryout of shuttle-puller coils, as with this type any kind of wire could be used. These had another advantage in that adjustable tools could be used to make accurately shaped coils.

The shuttle-puller coils had their limits, being applicable to certain combinations of wire sizes, turns per single coil, number of single coils per slots, coil pitch and armature diameter. The result was that few shuttle-puller coils were used in railway armature windings.

Thus, for awhile, multi-turn coils for large ratings were not obtainable unless square or round wire was used, as it was difficult and expensive to use bare copper strap or ribbon. More turns, of course, meant more commutator bars.

To fill this gap, the double-loop coil, Fig. 8, was developed. The double loop at the rear overcame the difficulty experienced with ribbon wire, in bending the leads widthwise, and allowed the top lead to be brought from the top and the bottom lead from the bottom of the coil. Thus both leads are in the proper plane, and can be, and are in most cases, shaped to fit directly into the proper commutator neck. Furthermore, one to five turns per coil can be had with ribbon or bare copper strap, which is important.

During the development of the strap-copper coils, it was found that, with the larger coils, considerable difficulty was experienced in winding the armatures. This lead to the use of half or two piece coils, Fig. 5. This type has the further advantage of ease of repair, as a damaged bottom coil, can be reached by removing a few top coils, whereas with one piece coils, a throw and a third must be raised in some cases to remove one coil, and often the coils so raised are ruined.

Type designation of coils is based upon the shape of the end windings. It is interesting to note that every coil type mentioned here is still employed in various forms in modern motors, both railway and industrial.

Each type of coil can be made in various ways, but there is one method best suited to each. The method to use is the one that reduces strains and pressure to a minimum, gives a smooth and rigid slot section, allows good penetration of varnish, and insures self-supporting turns. Close attention to small details is essential to produce first class coils, and as a means to this end, proper tools, fixtures, presses, etc., are an absolute necessity.

*See Figs. 2 and 6 pp. 490 and 491 of the JOURNAL for October, 1928.

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# Fundamentals of Magnetic Blowout Structures*

L. G. RILEY.

### OSCILLOGRAPH STUDIES

In order to study simultaneously the current and voltage changes during the arc-rupturing period, and their relation to the movements of the actuating mechanism, use has been made of an oscillograph recording line volts, contact volts, load amperes, operating coil volts and the mechanical movement of contacts, the last named also acting as a timing wave. Such a test record on a 1000 ampere unit is shown in Fig. 11.

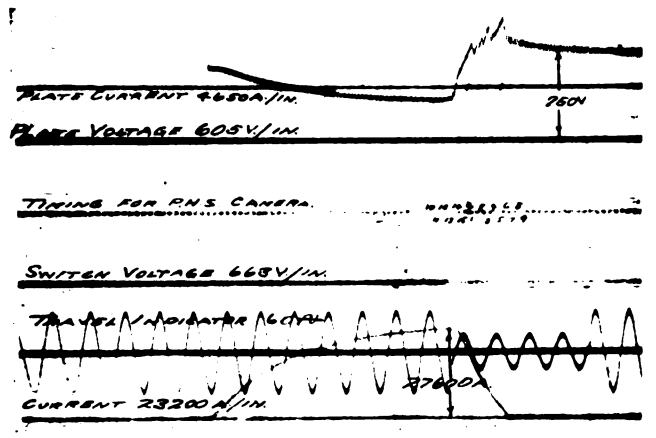


FIG. 11—AN OSCILLOGRAM OF AN ARC-RUPTURING TEST ON A 1000 AMPERE SWITCH

One of a series of typical curves plotted from such oscillograms is shown in Fig. 12. These are all plotted against the current at the instant of contact separation. Curve *A* shows the time from the instant the magnet exhaust valve lifts, to the separation of the contacts. This shows the time taken for the exhaust valve port to reduce the pressure in the cylinder to the point where the opening spring starts to accelerate the moving parts. Since all of these tests were run at the same air pressure and with the same air valve, the decrease in time at the greater currents can be caused only by the increase in the electrodynamic forces produced by the current in the switch. As the shape of the current path is an approximate loop, the natural tendency is to force the moving contact down.

Curve *B* shows the duration of the arc. At the very low currents, considerably below the rating of the switch, this time is longest due to insufficient magnetic-blowout action. As the current is increased, a minimum time of 0.02 seconds is reached at 3000 amperes. Beyond this point the time is gradually increased with the increase in arc energy. Curve *C* shows the overall time of the completed operation and is the sum of the other two. The time for this switch is practically constant at 0.12 second for a range from 1000 to 35 000 amperes. The curve is one of several that can be plotted to show the exact time of all the actions taking place during the opening of a switch. The timing wave, by change in amplitude, shows important points in the mechanical movement of the contacts, indicating a rate of separation of 13 inches per second. It is interesting to note that while the total contact separation may be ¾ inch or more, the arc is completely extinguished when the contacts are ⅛ to ¼ inch apart. The record also shows values of the over voltage in the arc, as increasing to more than double the line voltage at heavy currents. Oscillations in the arc voltage during the 27 000 ampere test indicate arc re-establishments, although the current curve is smooth, with a slight increase in slope toward the end. Synchronized photographs of the arc outside the box are shown in Fig. 13, and the successive arc streams or re-establishments are clearly recorded in exposures 1, 3, 4, and 5.

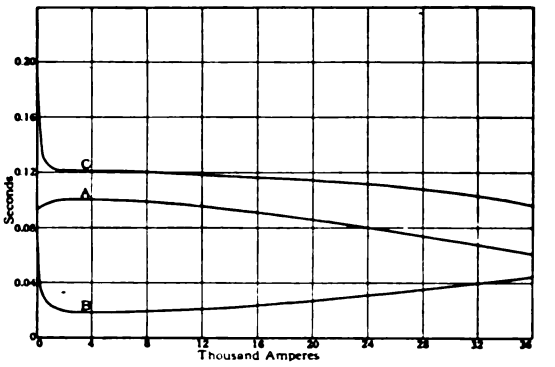


FIG. 12—TIME OF SWITCH OPERATION

Curve *A*—The time from de-energizing of the magnet valve to the instant of contact separation.

Curve *B*—The duration of the arc.

Curve *C*—The overall time and is the sum of curves *A* and *B*.

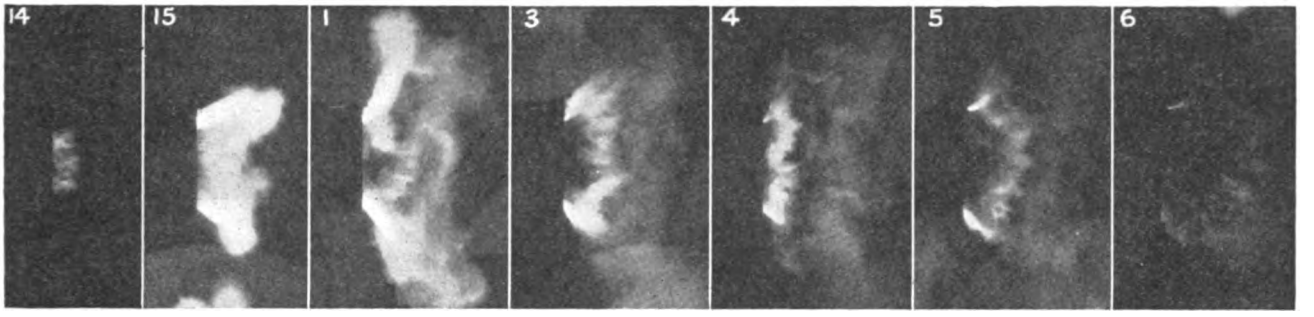


FIG. 13—SYNCHRONIZED PHOTOGRAPHS OF AN ARC

The numbers correspond to those on the timing wave in Fig. 11.

*Continued from the JOURNAL for October, 1928, p. 485.

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### BLOWOUT FLUX DENSITIES

For the purpose of comparison, studies were made on several units of different sizes, opening loads at current values near to the average each unit might be expected to handle frequently in service. A typical oscillogram with data as to test conditions is shown in Fig. 14. The effects of variable contact speeds, flux

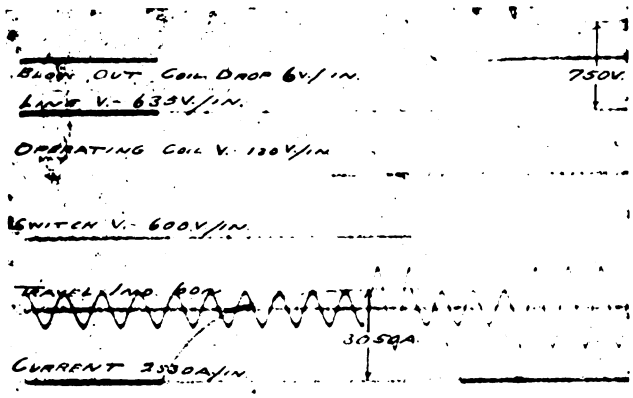


FIG. 14—AN OSCILLOGRAM OF AN ARC-RUPTURING TEST ON A 600 AMPERE SWITCH

density, and reactance can be determined in specific cases by adjusting each of these in turn and observing the result in time of arc duration and percent of over voltage during the arc-rupturing period.

Integration of these curves permits a tabulation of the switch characteristic* and the arc energy in watt-seconds, which is a direct measure of the gas volume

### SUMMARY

The purpose of the investigations outlined in these pages has been to determine the values and proportions of arc-box areas, flux densities, contact speeds, and other related details which will give maximum life and reliable service with a minimum of maintenance.

Arcs resulting from interrupting traction-motor loads must be broken in air by magnetic-blowout

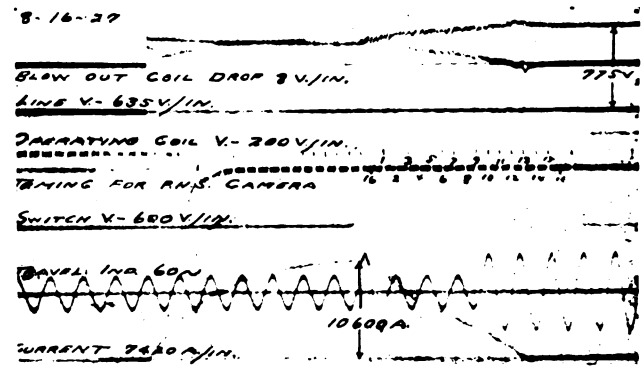


FIG. 15—AN OSCILLOGRAM OF AN ARC-RUPTURING TEST ON A HEAVILY LOADED 300-AMPERE, CLASS C BLOWOUT SWITCH

switches, combining the functions of stretching and cooling the arc stream in a limited space. Gases must be confined to prevent contact with grounded structures.

There are four well recognized forms of series blowout structures, each having a definite field of application. Contact separation varies from 5/8 to 1.5 in. depending on whether the line voltage is 600, 1500 or

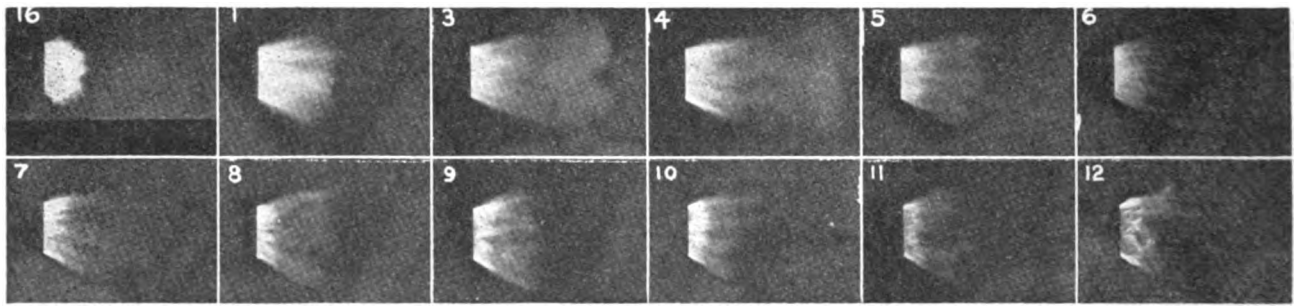


FIG. 16—SYNCHRONIZED PHOTOGRAPHS OF AN ARC
These pictures were taken at the rate of 160 exposures per second. The numbers correspond to the numbers on the timing wave of Fig. 15.

to be handled, and the degree of destruction to be expected on arc-horn surfaces and arc-box linings.

A typical example of undesirable arc re-establishment at high currents is shown in Figs. 15 and 16. The oscillogram shows re-establishments of such rapidity that the effect on the photograph is that of a steady stream of gas. Such a condition is allowable in a fuse box where a portion of the fuse is destroyed, which accounts for the prolonged breaking period; but in a switch structure this condition is not satisfactory and indicates the necessity for greater contact speed, more magnetic-pole area, and higher flux density on overloads.

*A detailed analysis of the arcing characteristics of switches is developed by Dr. R. Rüdenberg in part B of his book "Elektrische Schaltvorgange".

3000 volts, and the average rate of separation should be 10 inches per second or more.

Flux densities and points of saturation are indicated by curves. A safe maximum figure of flux density can be taken at 1000 lines per square inch at 50 percent of rated load, at high voltages. One-half of this is sufficient for average 600 volt duty.

The results so far obtained indicate that there are numerous possibilities of effecting further economies in design by more elaborate investigations of such factors as contact speeds, arc-box materials, baffles for confining and cooling of gases, flux densities, lag in flux collapse, load-limiting resistances, overload and no-voltage protection, and fuller use of the simpler classes of structures.

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# A New Type of Transformer Tap Changer

R. M. FIELD
Transformer Engineering Dept.,
Westinghouse Electric & Mfg. Co.

A NEW type of transformer tap changer has been developed for use in changing transformer taps, primarily as the result of a demand for a tap changer which could be applied to extra high voltage circuits. As the voltage of the transformer winding to which tap changers were connected increased, the problems of insulation became more difficult, and it was desirable to develop a tap changer with moving and stationary contacts of well rounded surfaces, thus decreasing the voltage gradient at the contacts.

A tap changer for 132 kv circuits is shown in Figs. 1 and 2. The stationary contacts consist of heavy brass rods of sufficient diameter to carry the current of the transformer winding, and to provide a low voltage gradient at the surface of the contacts. These stationary contacts are mounted in two insulating boards and are bridged by two moving contacts. Slots are provided in the insulating boards to permit the use of a small board with ample insulation distances. The moving elements are made in the form of a section of an annular ring with contact surfaces of a radius comparable with that of the stationary contacts. The moving contacts are not rigidly attached to the operating shaft of the tap changer, but are mounted so as to slide and roll on the stationary contacts while making a tap changing operation. Fig. 3 illustrates the details of construction. The two moving contacts are connected by a pin mounted in a slotted arm, the pin being capable of moving in a direction towards the operating shaft when the springs are compressed.

Adequate contact pressure is maintained between the moving and stationary contacts by means of the two heavy compression springs. In operating the tap changer from one position to the next, the moving roller contacts slide on the stationary rods and move towards the center, compressing the spring. The electrical connection between the two stationary contacts

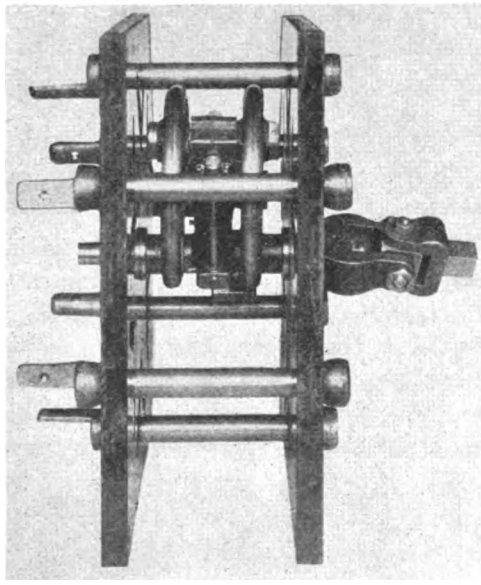

FIG. 1—A TAP CHANGER FOR 132 KV SERVICE

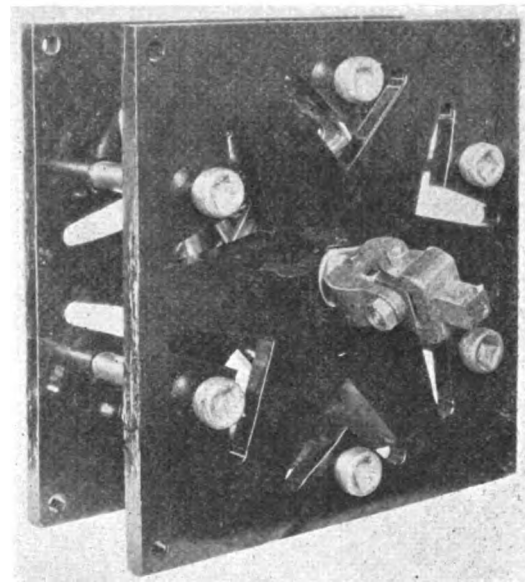

FIG. 2—THE TAP CHANGER BOARD IN DETAIL

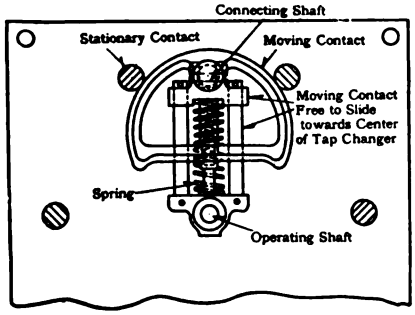


FIG. 3—THE ARRANGEMENT OF THE TAP CHANGER

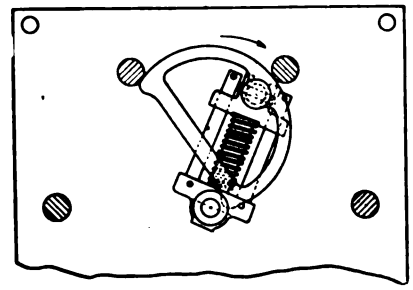

FIG. 4—THE TAP CHANGER SHOWING THE INITIAL MOVEMENT OF A TAP CHANGE

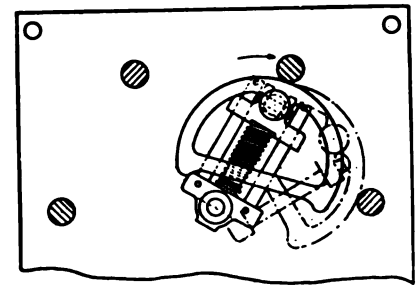

FIG. 5—THE TAP CHANGER IN UNSTABLE EQUILIBRIUM DURING A TAP CHANGE OPERATION

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is not broken until the center line of the moving element has passed the stationary rod, when the spring expands rapidly, throwing the rollers into contact with the next stationary member. The sliding action is then repeated as the rollers move into the central operating position. Figs. 4 and 5 illustrate the movement of the moving contact during a tap changing operation. The sliding action of the contacts produces a positive wiping action which cleans the contacts of dirt, sludge or other foreign material.

An important feature of this tap changer, in addition to the wiping action of the contacts, is the throw or flopping action of the moving contact. As soon as the center line of the moving contact has passed the stationary contact rod, the tap changer is in unstable equilibrium and the moving contact tends to throw itself into the new position without further movement of the operating hand wheel.

Since both the moving and stationary contact surfaces are of finite radius, the contact between the two

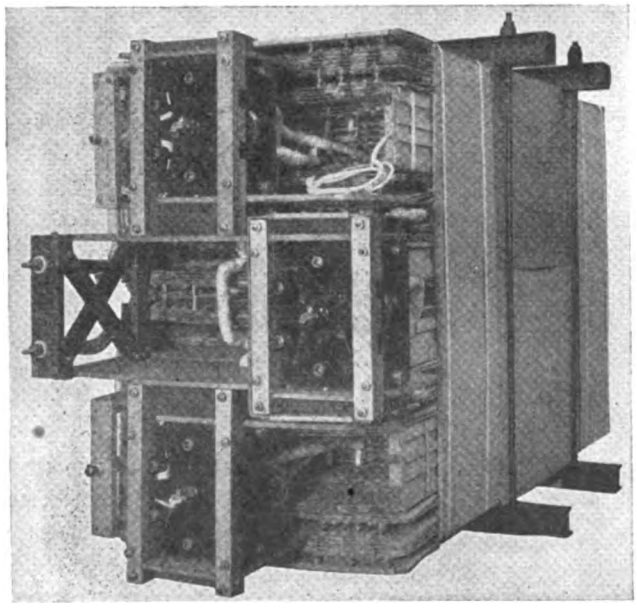

FIG. 6—A TAP CHANGER MOUNTED ON A SHELL TYPE TRANSFORMER

surfaces is theoretically a point contact. Practically, there is some area of contact, but the current carrying capacity of the contact depends almost entirely on the contact pressure and it is, therefore, only a matter of selecting a proper spring to give the required pressure between contacts for a given current rating.

When applied to the shell form of transformer this tap changer is mounted on an extension of the fullerboard washers, Fig. 6, and becomes an integral part of the transformer. The tap changer may be operated from the cover or from the side of the tank*.

While this type of tap changer was primarily developed for use with high-voltage, large, power transformers, it is also readily adaptable to low-voltage, small, power and distribution transformers. Fig. 7 shows a tap changer for 33 000 volts and 150

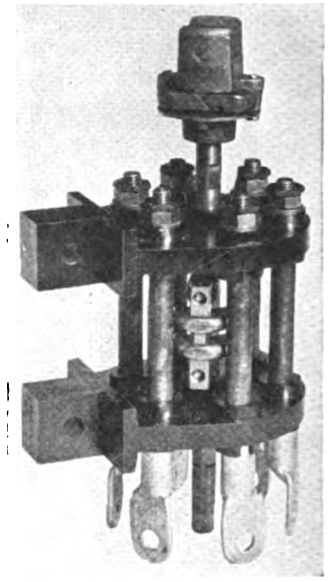

FIG. 7—A 33 000 VOLT, 150 AMPERE TAP CHANGER

amperes. The principles of design are the same as for the tap changer described above. The shape and small size of this tap changer also makes it especially adaptable to core form transformers as shown in Fig. 8.

Life tests on both the large and small sizes have been made, consisting of over a million tap changing operations, which is far in excess of the number of

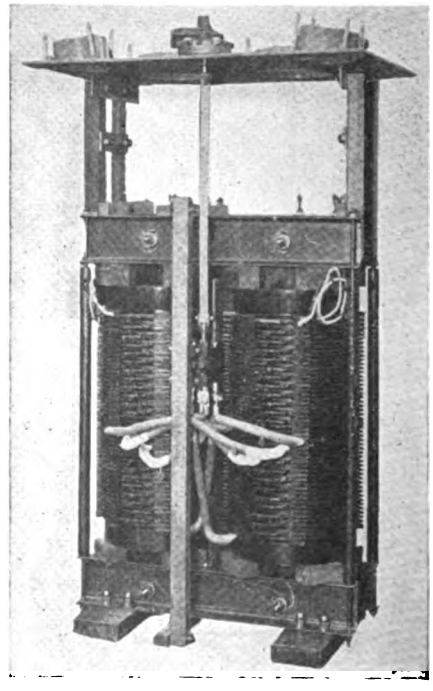

FIG. 8—A TAP CHANGER MOUNTED ON A CORE TYPE TRANSFORMER

operations which would occur in service. These tests have failed to show any signs of weakness in the design; in fact, the contacts were found to be in as good condition at the end of the test as at the beginning.

*Interlocked Mechanism for Tap Changers, R. M. Field, *Power Plant Engineering*—Mar. 15, 1927.

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# Oscillography*

## X—Sphere of Applications Expanded with New Galvanometers

JOSEPH W. LEGG

RECORDING human intelligence with an oscillograph seems to be even more fanciful than locating oil without drilling. However, the oscillograph has proven itself capable in each of these cases. Extensive tests in the State University of Iowa, have shown an astounding correlation between intelligence and speed in conduction of the nerve impulse in a reflex arc.** Dr. Travis used a portable three-element oscillograph for these tests, but a later model of the

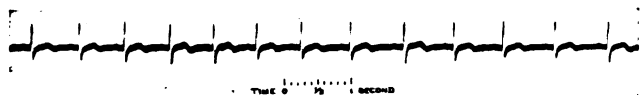

FIG. 1—ELECTROCARDIOGRAM TAKEN WITH BODY TRANSFORMER AND ONE-STAGE AMPLIFIER

Taken at a usual film speed of one inch per second. The variations in time between heart beats can easily be seen.

Osiso with a new galvanometer, can be used to greater advantage for such work.

Several new galvanometers have been developed which greatly simplify the recording of any phenomena which require the use of vacuum-tube amplifiers. These galvanometers function on a small fraction of the energy and a very small fraction of the current of those used for commercial testing in power plants, electrical laboratories, technical schools, etc. The vibrator used by Dr. Travis is the so called sensitive vibrator which consumes one-fifth the current of the standard vibrator, and responds to half the range of frequencies.

A new high-sensitive vibrator has been developed for the simplified Osiso. This vibrator consumes ap-

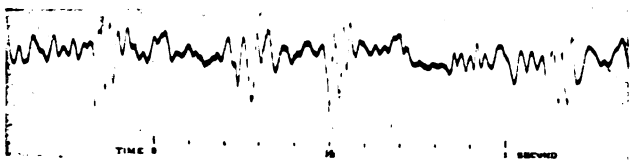

FIG. 2—PHONOCARDIOGRAM TAKEN WITH ULTRA-SENSITIVE GALVANOMETER

This record of heart sounds, during breathing, was taken at a speed of five inches per second. On the orginal film, frequencies of 250 cycles per second show clearly.

proximately one-tenth the current of the standard and yet responds to more than half as high a frequency. This vibrator is somewhat more delicate than the standard or sensitive type and is not recommended for power circuits where greatly abnormal currents may occur to destroy the fine ribbon forming the parallel strips of the moving coil.

A new super-sensitive vibrator has also been developed consuming less than one-thirtieth as much current as the standard and responding to one-fourth as high a frequency. Yet this vibrator will cover the whole range of body potentials, including the low frequency of heart potentials and the relatively high-frequency nerve impulses which control voluntary movements of the human body. This new super-sensitive vibrator will also cover the whole range of heart sounds. Thus it is suitable for making electrocardiograms, neurograms and phonocardiograms, when used with the proper vacuum-tube amplifier.

The troubles with vacuum-tube amplifiers increase greatly with the number of tubes and the amplification per stage. Hence, it is desirable to have much more

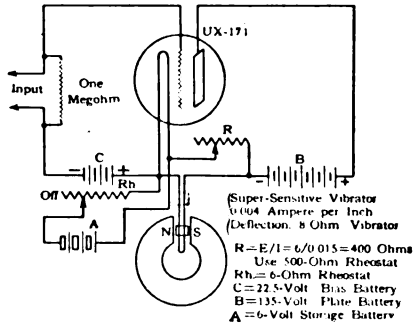


FIG. 3—A SUPER-SENSITIVE VIBRATOR WITH A SINGLE-TUBE AMPLIFIER AND DIRECT-CURRENT COMPONENT NEUTRALIZER

efficient galvanometers than those developed for electrical-engineering investigations.

A still more sensitive galvanometer has been designed which will even give a record of one microampere alternating current at any frequency from one cycle per second to nearly 1000 cycles per second. Furthermore the deflection for the same current is very nearly constant for all frequencies up to 500 cycles per second. This gives a deflection proportional to the instantaneous value of current from the smallest readable deflection to full-scale value. It is a real instrument and not a mere indicator operating on the saturated-vane principle. Without the great magnetic strength and permanence of cobalt steel, in small sizes, this galvanometer would be impossible. Furthermore this remarkable ultra-sensitive galvanometer will stand several thousand percent overload, for a short period, without harming it. It is more rugged than the super-sensitive or high-sensitive galvanometers. In some ways, it is more rugged than the sensitive or even the

*The nine preceding articles were: I—Description of Reflected-Beam, Incandescent-Lamp Oscillographs, June, 1927; II—The Osiso, July, 1927; III—The Osiso as a Phonoscope, Aug., 1927; IV—The Osiso Exhibitor, Sept., 1927; V—The Two-Element Power Osiso, Oct., 1927; VI—The Multi-Element Oscillograph, Nov., 1927; VII—Transmission Line Studies With the Multi-Element Oscillograph and Power Osiso, Dec., 1927; VIII—Apparatus and Procedure for Staged Tests, Jan., 1928; IX—Polyphase Galvanometer Control for the Multi-Element Oscillograph, Feb., 1928.

**See "Science" for January 13, 1928, pp. 41 to 43 by Dr. Lee Edward Travis, fellow of the National Research Council.

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standard galvanometers. Its only disadvantage is that it is not non-inductive, but when located in the plate circuit of a vacuum tube the impedance of the galvanometer is usually considerably less than that of the tube at all frequencies being studied.

This ultra-sensitive galvanometer has made possible a stable direct-current amplifier of but three vacuum tubes, which will show a direct-current change of potential of ten microvolts, in the grid circuit of the first tube. Nerve potentials can be shown with but two vacuum tubes in the amplifier, provided a suitable input transformer is used between the patient and the grid of the first tube. The potential from arm to arm or arm to leg of a normal human being is from 1 to 2 millivolts peak at each heart beat. The voluntary nerve potentials are sometimes greater and sometimes less than this, but their frequency is usually as much as fifty times as great. The Osiso, with an ultra-sensitive galvanometer, will cover fifty times the frequency and fifty times the film speed of any standard electrocardiograph, and yet the photographic record will be sharp and distinct. Furthermore, two simultaneous records can be made with two ultra-sensitive galvanometers in one Osiso. Six simultaneous records could be made with as many ultra-sensitive galvanometers in the multi-element oscillograph, on one film, at any speed between one inch per second and two feet per second. Three high-sensitive galvanometers may be added for the seventh and eighth and ninth places, thus giving nine simultaneous records.

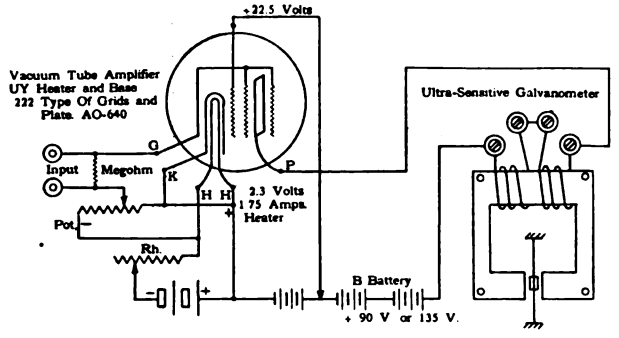


FIG. 4—THE CIRCUIT OF AN EXTREMELY SENSITIVE VOLTMETER

These galvanometers open up fields of investigation which were impossible before. Heart sounds and breathing may be recorded with a suitable microphone, step-up transformer, one-tube amplifier and an ultra-sensitive galvanometer, in either the Osiso or in the Multi-element Oscillograph. Also heart sounds and breathing may be recorded very accurately by the same microphone and transformer, but with a two-tube resistance-coupled amplifier, stepdown transformer and high-sensitive or super-sensitive galvanometer. It is the writer's belief that before many years photographic records of heart sounds and of breathing will be the standard method for diagnosis by all first-class physicians, especially in making a medical examination for life insurance, where a permanent record would be particularly valuable. All frequencies and wave-shapes present appear on the one film and may be analyzed later, at any time, by anyone skilled in this new art. No previous electrocardiograph was suitable for taking phonocardiograms (heart sounds) or stethograms (breathing).

Even the standard Osiso galvanometer, as well as the new high-sensitive one, does not require a very special amplifier. With the new super-sensitive and ultra-sensitive galvanometers the amplifier becomes as simple as that in any ordinary radio receiving set. Special high-grade iron such as hipernik, must be used in the transformers. If a direct-current amplifier is used with the ultra-sensitive galvanometer and a special microphone, then minimum distortion is introduced in the shape of the sound wave.

The new galvanometers are also very valuable in geophysical investigations, for locating oil domes (buried rock structures) in the gulf regions. Many of the standard and old sensitive galvanometers have been used for this purpose, but the new galvanometers will greatly simplify the seismicrophone and amplifier which transforms the minute vibrations of the earth into electric currents capable of operating the galvanometer. By choosing the proper impedances of galvanometer and vacuum tube it is easy to eliminate the higher frequencies of surface sounds and record the very low frequencies transmitted through many miles of earth as the result of the explosion of a charge of dynamite near the center of a circle formed by many seismicrophones and Osisos. Since sound travels from 2.5 to 3.5 times as fast in the salt dome as in the alluvial soil about it, it is easy to tell that the instrument recording the disturbance first is the one more nearly in line with the salt dome, which is almost certain to have oil pockets about its sides. Reflected sound waves and reverberations are also recorded and add valuable information to the records, which are examined by geological experts. Dynamite costs several hundred dollars a day per set of instruments, hence extra selective and extra sensitive instruments are very valuable. More oil bearing domes have been found by this general method of exploration per week (on the average) than per year by random drilling. The by-product (sulphur, etc.) of one dome was sold for over a million dollars. Oil men familiar with the findings of this method state that the present price of gasoline would be very much higher if it was not for the success of this method of exploring. It is not necessary to drill at present when the seismograms have disclosed the exact contour of the dome, so that the oil company may purchase all oil rights on the land above. Anticlines are also located in other sections of the country by the echo method, a double echo occurring over the rock cleavage. Results are most easily obtained when the upper surface is alluvial soil and the irregularity in the rock formation (where oil is apt to be found) is not over 1000 ft. beneath the present surface of the earth. Greater depths require larger charges

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of dynamite and more selective instruments. These new galvanometers are many times as good for this purpose as any others.

An example is shown in Fig. 4 of the extreme simplicity of an oscillographic thermionic voltmeter, or microammeter, consisting of one shielded-grid vacuum tube, preferably of the indirect heated cathode type, and an ultra-sensitive galvanometer with 20 000 turns. A deflection of approximately one inch is obtained in the Osiso with this combination when the grid is changed but 20 millivolts. It should be noted that the outer (shield) grid becomes the control grid and that the inner grid (terminal at top) is connected to + 22.5 volts. Also the grid bias for the input must be between ¼ and ½ volt negative and not 1.5 volts if it is desired to obtain the best results. The potentiometer supplies this proper bias. A megohm resistor should be placed across the input binding posts so as to prevent the grid potential from floating away if the input circuit is opened. The heater must be supplied with direct current for best results. A deflection of 20 millivolts per inch, or 8 millivolts per centimeter, with only one vacuum tube and with an accurate frequency range from direct current to over 500 cycles per second, opens up entirely new possibilities.

Most galvanometers would be useless in the plate circuit of this shielded-grid tube, since the plate current is only 1 milliampere, or thereabouts, and since the characteristic of grid volts plotted to plate current does not remain a straight line over more than a fraction of a milliampere. However, since these ultra-sensitive galvanometers consume only 50 microamperes per inch (or 200 microamperes per inch for the less sensitive ones) they can be operated on the straight part of the characteristic and thus give faithful records of vibrations in grid potential over the full-scale range of the Osiso.

The new, extremely sensitive vibrators are made possible by the balanced construction of the spring lever. This feature, original with these instruments, has been used for a decade and has eliminated change in sensitivity due to shocks encountered while moving the instrument. The hard-silver ribbon which is used as the coil in each high-sensitive or super-sensitive vibrator is very much finer than that used in the sensitive or standard vibrator, and yet the balanced construction of the tension lever is such that the fine ribbon is not ruptured by ordinary shocks. In all previous designs the rod or spring connected to the tiny ivory pulley had so much unbalanced mass that its inertia ruptured the vibrator ribbon during the most careful shipment.

A still smaller mirror is used with these very sensitive vibrators. Approximately 3000 of these are cut from one square inch of very thin, silvered glass. Nevertheless, the records made with these mirrors in an Osiso are sharp and clear.

The high-sensitive vibrator responds to higher frequencies than the sensitive vibrator and yet consumes but one-fourth as much current and is strung on bridges only half as far apart.

The greater sensitivity is very valuable when these vibrators are used in conjunction with a double-acting carbon pile for recording instantaneous pressure, vibration, extension, compression, acceleration, impact, etc. Such tests are often made in moving locomotives, automobiles, airplanes, submarines, battleships, elevators, etc. The oil damping and short bridge spacing of these vibrators greatly reduces their tendency to tremble and to give jagged curves when operated on such moving objects.

A radically new vibrator is the twin, consisting of two separate vibrating coils between two ivory bridges mounted on one frame having four terminals on top. This vibrator operates in the air-gap of a permanent magnet. The gap is about 80 percent greater than that in standard galvanometers, and yet each vibrator is approximately twice as sensitive as a standard vibrator, or 60 percent less sensitive than the sensitive vibrator.

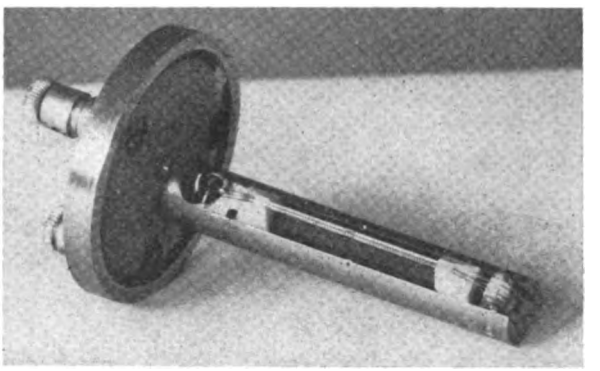

FIG. 5—THE TWIN-VIBRATOR ELEMENT

This has two moving coils with a tiny mirror on each. These fit in between the pole tips of one permanent magnet.

This twin vibrator makes possible the new 3 and 4-element Osisos, the former having one oscillographic wattmeter and one twin galvanometer, while the latter has two twin galvanometers. These twin vibrators are very satisfactory for making power circuit records with the automatic Power Osiso, where each vibrator is fed from the secondary of a 110 to 1.1 volt transformer or from one of the 5-ampere shunts included in the Osiso. Each of the 3 or 4-element Power Osisos includes at least one twin galvanometer and a positive (or negative) phase-sequence network, together with a triplet-transformer panel and proper adjustable resistors. The other galvanometer may be of the twin type or of the single-phase instantaneous, or single-phase average-value, or polyphase instantaneous, or polyphase-average-value type. This gives five different models especially suitable for power transient recording.

A new full-automatic-operation panel has been developed to operate lamp, motor, relays, and thermo-

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static cutout all on one 6-volt storage battery. To complete requirements for a simple, self-contained outfit a 6-volt motor has been added directly to a slow-speed long-film holder with worm gearing arranged to drive the film approximately 3 in. per second. This whole outfit is shown in Fig. 6, and is the last word in compactness and simplicity for a true oscillograph giving 3 or 4 simultaneous records of chance disturbances. Besides giving wonderful definition of records this outfit operates in a remarkably short time after its inception by abnormal current caused by a flashover or other fault in the power system. The one-half ampere lamp lights sufficiently to give a photographic record in 0.02 second after the closing of the initiating relay. The total delay in starting a record may be as small as 0.03 second from start of abnormal current in initiating relay, and within 0.1 second from start the film is at full speed. In fact, the third cycle of a 60-cycle short-circuit is photographed, stretched out so as to show its wave form and harmonics. All of this is done with the outfit, shown in Fig. 6, supplied from any 6-volt storage battery or from 8 to 12 dry cells connected in series parallel. Furthermore the apparatus operates repeatedly without any attention and functions differently according to the type of disturbance which initiates it.

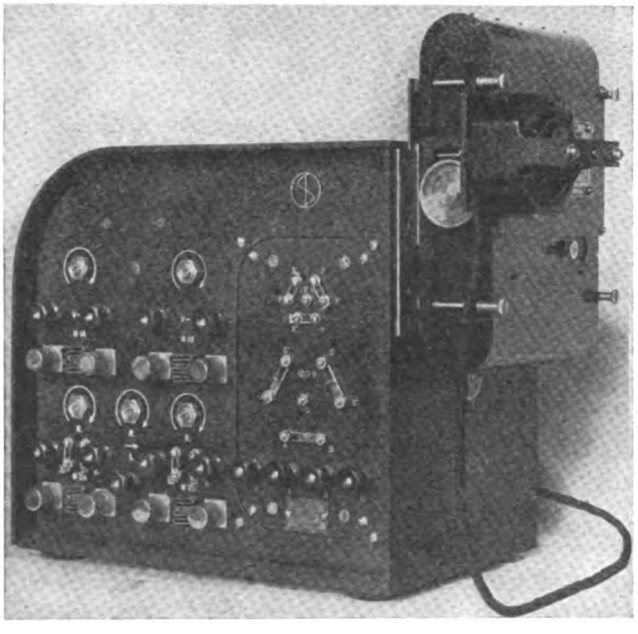

FIG. 6—THE COMPLETE FOUR ELEMENT POWER OSISO

With triplet-transformer panel and motor driven film holder.

These new three or four-element outfits with motor-driven film holder are not as extremely flexible for all testing as the two-element models having independent vibrators and larger external motors with pulley and gear reduction units. However, the newer models will be found to be more popular with the central-station engineer for 90 percent of automatic recording of transmission-line and generating-apparatus disturbances.

## CHOICE OF APPARATUS

In the days when there was but one oscillograph made in any one country there was, of course, no choice, and aside from a few large electrical concerns, few people even considered using such an instrument.

TABLE I—GALVANOMETER CHARACTERISTICS

| Type of Galvanometer | Direct-Current Consumption | Ohms | Natural Frequency Cycles | Used in Instrument |
|---|---|---|---|---|
| Standard Vertical | 0.18 A/in. | 0.9 | 5000 | Vertical Osiso |
| Standard Vertical | 0.13 A/in. | 0.9 | 5000 | Lab. Multi-El. |
| Standard Horisontal | 0.14 A/in. | 0.7 | 5000 | Std. Osiso |
| Standard Horisontal | 0.10 A/in. | 0.7 | 5000 | 7th, 8th and 9th |
| Sensitive Vertical | 0.04 A/in. | 1.3 | 2500 | Power Osiso |
| Sensitive Vertical | 0.03 A/in. | 1.3 | 2500 | Power Multi-El. |
| Highly Damped (Fin.) | 0.06 A/in. | 1.3 | Damped | Test Osiso |
| Highly Damped (Fin.) | 0.04 A/in. | 1.3 | Damped | Test Multi-El. |
| High-Sens Vertical | 0.008 A/in. | 8 | 3000 | Physical Osiso |
| High-Sens. Vertical | 0.006 A/in. | 8 | 3000 | Physical Multi-El. |
| High-Sens. Horizontal | 0.006 A/in. | 6 | 3000 | Physical Osiso |
| High-Sens. Horisontal | 0.004 A/in. | 6 | 3000 | Physical Multi-El. |
| Super-Sens. Vertical | 0.003 A/in. | 8 | 1300 | Vertical Osiso |
| Super-Sens. Vertical | 0.002 A/in. | 8 | 1300 | Lab. Multi-El. |
| Twin Vibrator | 0.08 A/in. | 1.3 | 2500 | 3 or 4-El. Osiso |
| Twin Vibrator | 0.06 A/in. | 1.3 | 2500 | 15 El. Oscillograph |
| Ultra-Sensitive | 0.3 MA/in. | 1 000 | 700 | Physiological Osiso |
| Ultra-Sensitive | 0.2 MA/in. | 1 000 | 700 | Physio. Multi-El. |
| Ultra-Sensitive | 0.07 MA/in. | 20 000 | 700 | Physiological Osiso |
| Ultra-Sensitive | 0.05 MA/in. | 20 000 | 700 | Physio. Multi-El. |
| 1-Phase Inst. Watt. | 0.3 $A^2$/in. | 1.3 | 2500 | Power Osiso |
| 1-Phase Inst. Watt. | 0.2 $A^2$/in. | 1.3 | 2500 | Power Multi-El. |
| 1-Phase Average Watt. | 0.4 $A^2$/in. | 1.3 | Damped | Power Osiso |
| 1-Phase Average Watt. | 0.3 $A^2$/in. | 1.3 | Damped | Poewr Multi-El. |
| 2-Phase Inst. Watt. | 0.3 $A^2$/in. | 0.5 | 2400 | Power Osiso |
| 2-Phase Inst. Watt. | 0.2 $A^2$/in. | 0.5 | 2400 | Power Multi-El. |
| 3-Phase Average Watt. | 0.14 $A^2$/in. | 0.1 | Damped | Power Osiso |
| 3-Phase Average Watt. | 0.10 $A^2$/in. | 0.1 | Damped | Power Multi-El. |

The values of amperes per inch deflection, amperes squared per inch deflection, and ohms resistance are only approximate. The values of natural frequency in cycles per second are only approximate and refer to the undamped condition only. All vibrators are to be operated damped in oil. The example of instrument used that is given for each galvanometer is often but one of several which may use the galvanometer. In the case of each polyphase galvanometer the rating is made on the assumption that there is the same current in each phase, and that this is direct current. The maximum deflection for alternating current values of voltage or current is 2.83 inches for instantaneous vibrators and 2.0 inches for instantaneous wattmeters. The average value will be the same for alternating current as for direct current.

Today the application of the oscillograph has spread to people of varied training and requirements. Furthermore a choice may be made as to which of many instruments is the best for a particular application. Actually any one of the half-dozen different instantaneously-recording vibrators would be capable of showing voltage or current waves in alternating-current machines. That covered 95 percent of the field of application of oscillographs used in technical schools not so many years ago. Now we can record instantaneous watts, both single-phase and polyphase values, with one galvanometer! However, even the polyphase instantaneous-wattmeter becomes a good voltage or current recorder, when the current winding is excited with direct current and when one-half of the vibrator is used as in any constant-field galvanometer.

The various galvanometers are listed in Table I. This table should show the differences in their sensitivity, resistance and frequency. However, a little guidance may be advisable in choosing the most desirable galvanometer for the particular applications to be considered. One may say "Why not choose the most sensitive galvanometer for all applications, especially when its frequency range is so far beyond sixty cycles per second and even beyond the third or seventh harmonic of that commercial frequency." In most com-

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mercial alternating-current circuits it makes little or no difference whether the oscillograph vibrator takes two-tenths of a milliampere or two-tenths of an ampere. Certainly it is seldom required that the current taken by the oscillograph vibrator be less than five hundredths of an ampere. In general, either the standard

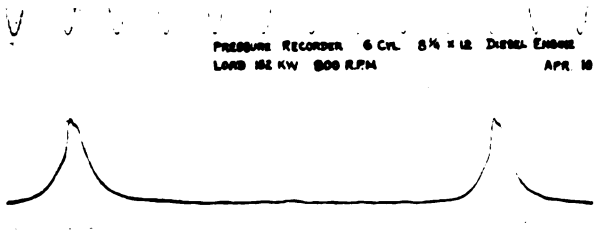

FIG. 7—AN OSCILLOGRAM OF INSTANTANEOUS PRESSURE IN AN INTERNAL COMBUSTION ENGINE

or the sensitive vibrator is fully sensitive enough for power circuit investigations; these have the advantage that they give better illumination on the film and are somewhat more rugged than the high-sensitive or super-sensitive vibrators. Also the resistance of the former is much less than that of the latter and the greater strength of the ribbon makes it easier for the average man to restring the vibrators, if necessary. The standard vibrator may be very highly protected by the spring fuse designed for this purpose so that a momentary current of even five amperes through the vibrator and fuse is cut off so quickly that the vibrator is not usually burned out. The greater-sensitivity elements cannot be so easily protected, nor so easily restrung in case they are burned out.

For physical investigations of minute movements, pressures, distortions in machines, vibrations in shafts, etc., it is often desirable to have a very sensitive galvanometer and yet have it capable of following rapid vibrations, etc. The high-sensitive vibrator is particularly valuable in such work. The auxiliary apparatus is often designed to give as much change of current as is possible, while still reproducing the instantaneous fluctuations in pressure, or movement, reliably. The greater sensitivity of the vibrator gives greater deflection on the film, and yet the vibrator is not in danger of a great over-current in such applications. The high-sensitive vibrator has proved to be particularly valuable in studying instantaneous pressures in internal combustion engines, through the medium of specially-constructed carbon disks acting in push-pull relation, so that the differential current passes through the vibrator.* The mere change from sensitive to high-sensitive elements gave a 500 percent increase in the size of the pressure-time curve without any sacrifice in frequency response.

For vacuum-tube investigations it is very desirable to have a galvanometer so sensitive that it may be used directly in the plate circuits, without requiring special amplifier tubes, and without disturbing the circuits. If audio frequencies are to be investigated the standard vibrator should be used when it is possible to use it with an extra transformer of the proper ratio, i.e., 2500 to 25 turns. However, when an extra transformer cannot be used, then it is usually desirable to use the high-sensitive vibrator since it consumes approximately one-twentieth as much current, and will give a good deflection with the audio-frequency change in plate current in one UX-171 radiotron, as well as in any of the larger vacuum tubes. Where greater sensitivity (and less range in frequency) is desired, then the super-sensitive vibrator should be used, since it draws a small enough current to be suitable for the plate circuit of a UX-201A radiotron or larger tube. This vibrator will show any low-frequency distortion, but will not cover the range of higher audible frequencies. However, it

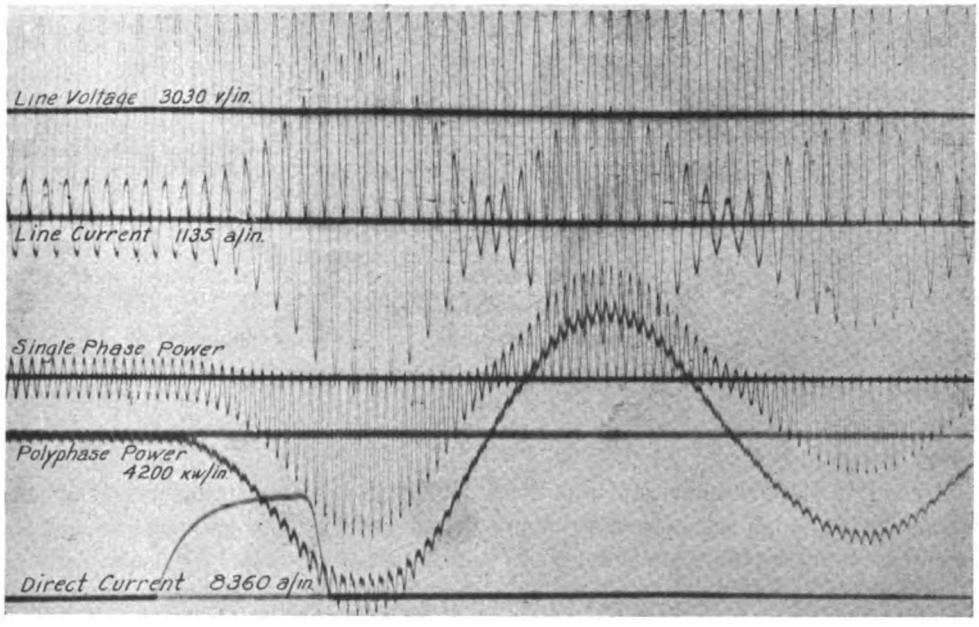


FIG. 8—AN OSCILLOGRAM TAKEN DURING A SHORT-CIRCUIT ON TH E DIRECT-CURRENT GENERATOR OF A MOTOR-GENERATOR SET

*See "A New Electrical Engine Indicator" *S.A.E. Journal*, July 1928, pp. 87-97.

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is ideal for all alternating-current rectifier circuits, as it may be used across a suitable shunt or placed in series with a non-inductive resistance of several hundred ohms per volt. It will thus record any current from a milliampere to many amperes and consume only a few millivolts, or it will record any potential from a few millivolts up.

TABLE II—GALVANOMETERS

| Type | Horizontal | Vertical | | | |
|---|---|---|---|---|---|
| Records | Volts or Amperes | Volts or Amperes | Microamperes | Watts | |
| Type of Vibrator | Standard or High Sensitive | 1—Standard<br>2—Sensitive<br>3—High Sensitive<br>4—Supersensitive | Permant Magnet Vane | Instantaneous | Average Value |
| Number of Vibrator Coils | Single Coil of Two Parallel Conductors | Single or Twin | None | Single or Double | Single or Double or Triple |
| Magnets (Stationary) | Permanent | Permanent | Wound Coil | Wound Coil or Coils | Wound Coil or Coils |
| Damping Fluid | Nujol or Mixture with Kerosene | Nujol or Mixture with Kerosene | Nujol | Nujol | Nujol |

Transient potentials of 220 000 volts, 50 cycles, may be studied by placing this vibrator in series with a running-water-column resistor of 100 megohms. Sensitivity is very valuable in such a case for even here the energy dissipated in the running water is nearly half a kilowatt, at such a high voltage. Rectified currents at several hundred volts may be studied easily with the super-sensitive vibrator. The vibrator circuit consumes but one watt at 500 volts direct current for one inch deflection. On alternating current the deflection would be more than two and a half inches, at this same watt consumption. Recently, wire-wound resistors, suitable for this work, have been placed on the market by several different manufacturers. These resistors have sufficient heat-radiating capacity, even at 100 000 ohms and more, to serve as series resistors for high-sensitive and super-sensitive vibrators when used to record transient potentials of several hundred volts.

Much apparatus developed for radio-receiving sets is adaptable to certain oscillograph problems. Rheostats, resistors, switches, transformers, batteries, rectifiers, etc., often may be used in whole or in part in developing auxiliary apparatus to broaden the application of the oscillograph both in the electrical and in the non-electrical field.

The ultra-sensitive galvanometer may be used as a voltmeter on higher potentials, only where a series resistance may be used which is very high compared with the reactance of the winding of the galvanometer. Usually this resistance should be a quarter megohm or more. At 50 microamperes this would represent 0.00005 × 250 000 = 12.5 volts. Thus, for 135 volts direct current, the galvanometer would require a series resistance of half a megohm to keep the deflection below 2.5 or 3 in.

It is thus seen that galvanometers are now available for use with available resistors to study vacuum-tube and small-rectifier circuits most accurately. Furthermore, these are not string galvanometers and have none of the disadvantages which are inherent with string galvanometers. Six ultra-sensitive records may be taken simultaneously on one daylight-loading film.

A very simple and highly efficient outfit for studying vacuum tube and B-eliminator circuits might consist of one high-sensitive and one ultra-sensitive galvanometer in a vertical-element Osiso. The twin galvanometer could be used in place of the high-sensitive one if neither of its vibrators are to be used to study frequencies above 500 cycles per second. At 1000 cycles and 2 in. deflection, one twin affects the other by about five percent, but at 120 cycles there is no measurable interference. Hence for rectifier work, or alternating current, the twin galvanometer may be used and thus increase the number of simultaneous records which may be taken with the Osiso. Care should be taken to have the twins at nearly the same potential.

TABLE III—AUXILIARY APPARATUS

| Resistors | Reactors | Transformers | Microphones | Converters |
|---|---|---|---|---|
| 1—Constant<br>2—Variable<br>3—Varying | 1—Inductive<br>2—Capacity<br>3—Tuned | 1—Potential<br>2—Current<br>3—Audio Frequency | 1—Voice<br>2—Music<br>3—Seismic | 1—Vibration<br>2—Pressure<br>3—Extension |
| Rectifiers | Amplifiers | Photo Cells | Thermometers | |
| Copper-Oxide<br>Mercury-Arc<br>Vacuum Tube | Direct Current<br>Impedance Coupled<br>Transformer Coupled | Light Recorders<br>Seismicrophones | Thermo Couples<br>Resistance Bridge | |
| Time Markers | Relays | Time Relay | Carbon Piles | |
| Glow Tube<br>Lamp Flicker<br>Stroboscope<br>Jump Spark | Over Current<br>Under Potential<br>Negative Phase | Shading Coil<br>Thermostatic<br>Gear Train<br>Change of Resistance | Instantaneous Pressures<br>Extensiometer | |

For studying interference in telephone lines and receiving sets the high-sensitive galvanometer should be valuable. Likewise its superiority should prove of value in studying telegraph circuits. For physical, geophysical and physiological investigations where very low voltages and minute currents are involved, the ultra-sensitive galvanometer will be found to be a tremendous improvement on any other galvanometer ever used. One vacuum tube and this galvanometer is a more sensitive combination than several tubes and any other galvanometer of the reflecting-beam type. One tube and this galvanometer, see Fig. 4, is approximately 30 times as sensitive as seven tubes and an old sensitive galvanometer.* This one tube arrangement with this ultra-sensitive galvanometer is also more

*As described in the August 1928 A. I. E. E. Journal, p. 594 to 597.

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sensitive than the direct-current amplifier consisting of two 5-watt tubes and one 75-watt tube developed at the United States Bureau of Standards to go with an older galvanometer. The ultra-sensitive galvanometer was developed to cover the relatively high frequencies met with in recording all voluntary and involuntary nerve potentials of the human body compared with the relatively low frequency potentials controlling the human heart at each beat. It will also respond to the relatively high frequencies met with in recording heart sounds, and hence is a universal galvanometer for taking electrocardiograms, neurograms, phonocardiograms and stethograms.

A long-time record of the volume or intensity of sound may be made by using an audio-frequency rectifier and the damped (fin type) element. The copper-oxide rectifier may be used in series with this sluggish element so that the resulting curve will be much easier to follow in case the record is a very slow one. The same damped element is particularly good for recording extension or compression of materials or machine parts when subjected to great stresses. This is accomplished by rectifying the wave modulated by the movement to be recorded, a change of capacity or reactance in an alternating-current circuit being the activator.

The choice of power galvanometers is more evident except that the single-phase instantaneous wattmeter shows kilovolt amperes, power-factor, and average power as well as instantaneous power. The three-phase average-value wattmeter is used only where four wires are active or where there is a ground current. The polyphase instantaneous wattmeter will show total power in a three-phase circuit breaker during test and show the unbalance of phases during a power surge.

# Methods of Testing Electrical Apparatus

## XXVII—Insulation Tests and Tests on Single-Phase Transformers not Self Cooled

### INSULATION TESTS

The transformer insulation tests commonly made are:—

1—Insulation resistance measurements.
2—Dielectric tests.
  a—Between the high-voltage winding and the low-voltage winding, the low-voltage winding being connected to the core and the case.
  b—Between the low-voltage winding and the core and the case.
3—Over-potential tests.

The insulation resistance of a transformer is of doubtful significance, as compared with the dielectric strength. It is subject to wide variation with temperature, humidity and cleanliness of the parts. The physical dimensions and coil grouping of a transformer also are factors that influence the insulation resistance. Furthermore, a transformer will invariably show a much lower value of insulation resistance when submerged in oil, than when out of oil, even though the dielectric strength of the oil is high. In general, insulation resistance cannot be taken as a real criterion of dielectric strength; however, it may afford a useful indication as to whether a transformer is in suitable condition for application of the dielectric test or for placing in service.

Insulation resistance measurements are perhaps most useful when drying out newly wound transformers, preparatory to impregnating with oil. In such instances, it is possible to obtain comparatively high values, 2000 megohms and above, with prolonged drying; however, such values will not be obtained after the transformer has been submerged in oil. Experience has demonstrated that insulation resistance values of one-half to one megohm per kv rating of a transformer, in oil, are indicative of safe values preparatory to making the dielectric test or placing a transformer in service, provided the dielectric strength of the oil meets the prescribed value.

### MEASUREMENT OF INSULATION RESISTANCE

The insulation resistance of a transformer can be measured either by the voltmeter method or the megger method.[1] The more convenient method is the megger method. The procedure is as follows:—Disconnect all temporary wiring from the transformer. Stand the megger on a substantial base, connect the line terminal of the megger to the proper winding of the transformer and the ground terminal of the megger to the transformer core or case. Rotate the handle of the megger in a clockwise direction at a speed of about 100 r.p.m. If the transformer has considerable capacitance, it is essential to maintain full speed on the megger for at least one minute before taking a reading.

TABLE LVIII—TRANSFORMER INSULATION TEST VOLTAGES

| Rated Line Voltage of Winding to be Tested* | Test Voltage** |
|---|---|
| 0 to 549 | 4000 |
| 550 to 4500 | 10 000 |
| 4501 to 50 000 | 2.1 × rated line voltage + 1000 volts |
| Over 50 000 | 2 + rated line voltage + 1000 volts |

*The rated line voltage is the voltage of the circuit to which the winding is connected in service.
**To be applied from each winding to the iron and to all other lower voltage windings for one minute. During these tests all windings with a test voltage lower than the one to be tested should be connected to ground.

Reasonable care should be exercised in insulating the lead which connects the line terminal of the megger to the winding of the transformer. However, it is

[1]Described in the JOURNAL for April, 1925, p. 191.

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usually necessary to insulate the lead from ground by means of a support, unless it is insulated for at least 2200 volt service and in exceptionally good condition.

### DIELECTRIC TESTS

The dielectric test is the only real method of demonstrating whether or not the insulation of a transformer is adequate for its specific purpose.[2] The voltage value to be applied in the dielectric test depends upon the rated line (circuit) voltage to which the windings will be connected in service and upon the operating conditions. Power transformers, excepting those having graded insulation should be tested under the conditions given in Table LVIII. The tests for transformers with graded insulation are described later. All tests should be made with the transformer in oil if it is an oil-immersed transformer, or in air if it is an air-cooled transformer. The frequency of the test voltage must not be less than the rated frequency of the apparatus being tested.

Any winding divided into groups for operation at ½, ⅓, ¼, etc., of maximum voltage will require special tests, as follows:—(a)—When the maximum voltage developed in the total winding is 0 to 1000 volts, the test between the parts of the winding should be at 2500 volts for one minute. (b)—When the maximum voltage developed in the total winding is over 1000 volts apply 200 percent of normal rated voltage. The time period of this test is usually five minutes.

When the low-tension windings are to be connected in three-phase double delta for six-phase converter operation or for interconnected star, the test between the sections of the low-tension winding should be 2500 volts for one minute.

If the over-potential test run is made from a three-phase supply, all of the phases may be tested simultaneously from the high-voltage windings to the low-voltage windings and the iron and from the low-voltage windings to the iron. If the over-potential run is made from a single-phase supply, each phase should be tested separately from the high-voltage windings to the low-voltage windings and the iron. At the same time connect to the core both windings of the other phases and the low-voltage winding of the same phase.

When the test voltage does not exceed 30 000 volts, no spark gap calibration is needed. A voltage reading in either testing circuit is satisfactory. When the test voltage is over 30 000 volts, calibrate the meter in the low-voltage circuit of the testing transformer, or the crest voltmeter with the spark gap connected in parallel with the transformer to be tested, unless a voltage transformer is used on the high-voltage side of the transformer. When making tests, the spark gap must be opened corresponding to a voltage not exceeding 110 percent of the test value for test voltages not over 250 000 volts and 107.5 percent for test voltages over 250 000 volts.

[2]See the JOURNAL for April, 1925, p. 191.

The tank must be solidly grounded during all tests. The connections between the core and case and testing transformer must be made with a wire or chain. No water pipe should be allowed as part of the testing circuit unless paralleled by a wire from the testing transformer to the transformer being tested. All contacts must form a good electrical joint.

The transformer should be completely assembled, that is, the cover and outlet bushings should be in place and the centering frames, terminal boards, etc., in their proper positions. The windings must be at the normal operating temperatures. This will not be less than 55 deg. C. or more than 85 deg. C. The dielectric strength of the oil should have an average breakdown value of not less than 22 000 volts, when tested with one inch flat disc electrodes, set 0.1 inch apart and with their axis in the same horizontal line. The lower end of the bushings, condenser type or otherwise, for oil-cooled apparatus should extend as far under the oil during the test as it does in service. The line leads of the respective windings must be short-circuited.

### PROCEDURE FOR DIELECTRIC TEST

Apply voltage to the testing transformer, using whichever method of control is best adapted for the particular case in hand. Raise the test voltage gradually to about one-half its value and keep it there for a short period of time. This will aid in dispelling any air that might have been taken in when filling with oil. Then, increase the voltage until the desired value is indicated. Maintain constant voltage for the specified period and then gradually decrease it to zero. Open the power switch immediately afterward. In testing from the low-voltage winding to the core and case, the same general precautions should be observed. In case of insulation failure, any remaining tests must be carried out, as specified, in order to determine whether any other defects exist.

### INDUCED DIELECTRIC TEST

For transformers having graded insulation, it is necessary to apply an induced test in the high-voltage winding, instead of the usual applied dielectric test between the windings and ground. This test applies particularly to transformers which are to be operated with one end of the high voltage permanently grounded without resistance, and having reduced insulation to ground, graded according to the voltage of respective parts of the winding above ground.

On single-phase transformers of either shell or core-type the procedure for the induced voltage test is as follows:—Ground the low-voltage windings in such a way that the part of the winding adjacent to the highest voltage of the graded insulation winding is at ground potential, or as near ground potential as possible, without having the voltage between these windings more than the voltage above ground. Test by inducing a voltage in the high-voltage winding such that the ungrounded terminal is at a potential above

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ground of 2.73 times the normal voltage developed by the winding, plus 1000 volts.

The test should be applied for one minute when the frequency of the test voltage is 120 cycles or less, unless otherwise specified. If the frequency is greater than 120 cycles per second, then the time period shall be reduced so that the equivalent cycles of a 120 cycle one-minute test is obtained.

On three-phase, shell-type transformers the procedure is as follows:—

*a*—Open the circuit of any delta connected winding by opening the connections so that each phase is electrically independent. Short-circuit the graded insulation winding of two phases by grounding their high-voltage outlet leads. Test the other phase with a single-phase supply, the same as for a single-phase transformer. Repeat the test on each of the other two phases.

*b*—Test between high-voltage terminals by inducing from a three-phase supply twice the rated line voltage, plus 1000 volts for one minute. If this test is difficult to apply, a single-phase test to produce test voltage between terminals should be made.

Because of the interconnected magnetic circuits a three-phase, core-type transformer with graded insulation cannot be tested as under *a* for the shell type. It will be necessary to give the test described in the first part of *b*.

*Measurement of Test Voltage*—When the induced test voltage does not exceed 60 000 volts, the spark-gap may be omitted from the high-voltage circuit. Otherwise the voltage applied should be checked by calibrating the voltage of the low-voltage circuit against a spark-gap having a series resistance of at least one ohm per volt, connected across the high-voltage winding. When making tests, the spark-gap must be opened corresponding to a voltage not exceeding 110 percent of the test value for voltages not over 250 000, and 107.5 percent for test voltages over 250 000.

### APPLIED DIELECTRIC TEST

Winding not permanently grounded to iron and any other windings should be tested at two times the voltage of the line to which the winding is connected, plus 1000 volts, for one minute. The minimum test voltage should be 5000 volts. During this test, all windings of a lower rated voltage than the one being tested should be connected to ground at both ends. When the windings are to be connected in three-phase delta, the test between the sections should be at 2500 volts for one minute. All applied dielectric tests should precede any induced tests.

### OVER-POTENTIAL TEST

The over-potential test is made to determine the effectiveness of the insulation between adjacent turns and layers, and also to determine whether the clearance between adjacent leads and the spacing of the terminals is sufficient. This test is always made after the dielectric test and, usually, is the final test. It is permissible to make other tests after the over-potential test, but, in every case, an over-potential test should follow. The over-potential test on power transformers is usually made at 200 percent of the normal rated voltage. The time period is five minutes, unless otherwise specified.

Any winding divided into groups for operation at ½, ⅓, ¼, etc., of maximum voltage requires special tests, as follows:—

*a*—When the maximum voltage developed in the total winding is over 1000 volts and there is only one multiple voltage, make the over-potential run at both the series and the multiple-voltage connections.

*b*—When there is more than one multiple-voltage connection, make the over-potential run with the series-voltage connections and at such multiple-voltage connections as are specified. There must always be one multiple voltage run.

In order to avoid over saturation of the iron and to enable the over-potential test to be made with moderate size testing equipment, frequencies higher than normal are generally employed. It is obvious that if the frequency is increased in the same ratio as the

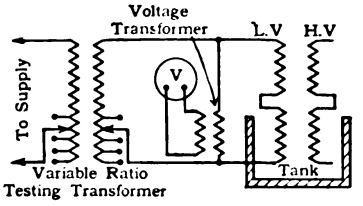


FIG. 127—CONNECTIONS FOR OVER-POTENTIAL TEST

voltage, the kv-a required to make the test, in any given case, will be the normal exciting kv-a, increased in the same ratio. The usual practice of one large transformer manufacturer is to use any suitable frequency not exceeding 133 cycles for air-cooled transformers, nor higher than 250 cycles for air-cooled transformers if more than 140 000 volts is developed in any winding by the test.

The procedure for the over-potential test is as follows:—See that all outlet leads are in their proper positions and that the terminal connections are properly made. Connect the transformer to an adjustable-voltage power source, as shown in Fig. 127. The variable-ratio transformer, if one is used, should be connected to give the greatest possible voltage range. Field control of the generator is preferred if it can be obtained. Start with a low voltage and gradually increase it until the specified value is indicated. Maintain a constant voltage during the test period and then gradually decrease to a low value before interrupting the circuit. The fact should be kept in mind that the characteristics of a core-type transformer are such that if an internal short-circuit should develop, it may not manifest itself in the usual manner. Frequent readings of the voltmeter during the test will guard against overlooking a defect of this kind, a falling off in the supply voltage being indicative of such a defect.

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SINGLE-PHASE OIFC TRANSFORMERS

Tests for single-phase, oil-insulated, forced-cooled transformers, except the temperature test, are practically the same as for the oil-insulated, self-cooled type[3], and should be conducted in a similar manner. The difference in the temperature test of the OIFC from that of the OISC is principally due to the method employed in cooling. The cooling is effected by circulating the oil from the transformer, through an external cooler, the oil flowing out near the top of the transformer, through the cooler, and back into the transformer at the bottom. Circulation of the oil is maintained by means of a pump capable of producing the required rate of flow. The cooler consists of a cylindrical cast-iron shell in which are assembled numerous brass tubes. The construction is such that the cooling medium water, passes through the tubes while oil is circulated through the shell. The cooling system must be capable of cooling the oil from a temperature of approximately 55 deg. to 40 deg. C. Suitable meters for indicating the rate of flow of oil, in gallons per minute, should be connected.

The temperature test should start at normal load and voltage, but without any circulation of the oil through the cooler until the oil temperature reaches approximately 55 deg. C. This may take three or four hours unless the test is started with hot oil. When the temperature of the oil has reached approximately 55 deg. C., start the pump in the oil circulating system and adjust the rate of flow to the specified amount in gallons per minute for the particular case. Turn on the cooling water and adjust the rate of flow so as to maintain the temperature of the entering oil at approximately 45 deg. C. Half hour readings should be taken of the temperature of the entering and outgoing oil and the rate of flow. Whenever possible, take temperature readings of the top oil at the center and well toward the side of the tank. These readings need be taken only during the latter part of the test. When shutting down the run, shut off the oil circulation by closing the valve in the entering oil line. At the same time, the power should be shut off. In computing the temperature rise by the increase in resistance method, the ambient temperature is assumed to be 20 deg. C. below the temperature of the entering oil.

TESTS OF SINGLE-PHASE OIWC TRANSFORMERS

As oil-insulated, water-cooled transformers similar to the oil-insulated, self-cooled type, except for the method of cooling, all tests other than the temperature test should be conducted in the same manner as described for the OISC type.

The temperature test is conducted similar to that described for the OISC type, excepting those features governed by the method of cooling. Since the method of cooling requires water to be circulated through cooling coils assembled inside of the transformer tank, every precaution must be taken to prevent water getting into the oil.

Before starting the temperature test, the cooling coils should be connected to the water supply and tried out to demonstrate that the proper rate of flow can be obtained, that all joints are tight and that everything pertaining to the cooling system is in good working order. In general, approximately 0.25 gallons of water per minute are required for each kilowatt of loss in a transformer.

The test should start with normal load and voltage but without any circulation of water until the temperature rise of the oil is about[4] ten degrees C. less than the temperature rise limit. After the cooling water is turned on, the flow through each pipe of the cooling coils should be so adjusted by individual valves that the outgoing water of each will have the same temperature. If in any case, it is found necessary to completely open the valve of any particular pipe, while the others are partly closed, it is an indication that the flow in that pipe is restricted, and the matter should be investigated at once. Particular attention should be given the cooling water which must be kept at the proper flow and temperature throughout the test. The total flow should be controlled by a valve in the main inlet pipe. Readings of the water flow and temperature should be taken at intervals corresponding with the other test readings and recorded on the temperature test sheets. Continue the test until the temperatures of the oil and the outgoing water have become constant. When shutting down the test, the cooling water must be shut off at the same instant as the power. In computing the temperature rise of the windings by the increase in resistance method, the temperature of the ingoing cooling water is taken as the ambient temperature. Any overload runs required should be conducted, as previously described*.

After all tests have been completed and the auxiliary piping has been disconnected, any water that remains in the cooling coils should be removed. The most convenient and satisfactory method of doing this is by connecting the cooling coils to a source of compressed air and blowing out the water.

SINGLE-PHASE, AIR-BLAST POWER TRANSFORMERS

Tests on air-blast transformers, except the temperature test, are conducted in practically the same manner as described for the OISC type. The temperature test is conducted in a manner similar to that described for the OISC, except for those features pertaining to the methods of cooling and obtaining the temperatures.

When setting a transformer on the air chamber, care should be taken that the supporting beams are properly placed to carry the weight of the unit and at

[3]Tests on OISC transformers are described in the JOURNAL in the issue for Sept., 1928, p. 457 and for Oct., 1928, p. 518.

[4]See the JOURNAL for Oct., 1928, p. 516.

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the same time not to interfere with access to the winding terminals nor restrict the flow of air. The dampers, doors and all other parts essential to confining and controlling the air must be in their proper places.

Thermometers should be placed on each transformer, as follows:—From six to eight on the coils, distributed over the high-voltage and low-voltage windings, one for the outgoing air and one in the air chamber. It is important that the coil thermometers[5] be properly held in place in such a manner that they will indicate the coil temperature rather than that of the cooling medium. This is accomplished by means of grooved sticks which can be placed in the ducts between adjacent coils without unduly restricting the air passage. The coil thermometers should be in place before power for the temperature test is applied and should be so placed as to permit temperature observations to be made without disturbing them. Mercury thermometers should not be used for the coils on account of the possibility of their breaking and the mercury getting into the windings.

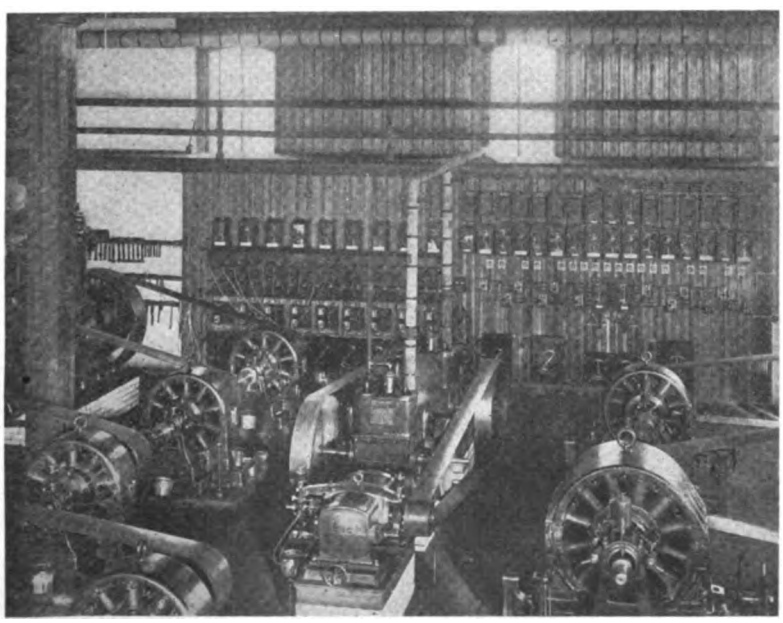
The air pressure and the volume in cubic feet per minute is usually measured by the Pitot tube method. When taking measurements to determine the volume of air passing through the transformer, the loss due to leakage around the air chamber cover and doors should be measured separately. The amount due to leakage should be deducted from the total measured volume with the transformer in place and its dampers wide open. The chamber loss is determined by closing the chamber as tightly as possible and measuring the leakage volume at rated pressure for the particular case in hand.

The temperature test is started by applying the normal magnetizing voltage and normal load current, but with no air for 20 or 30 minutes or until the coil thermometers indicate a rise of approximately 50 deg. C. Then start the blower. Adjust the air pressure of the chamber to the specified value for the particular case in hand. In general, the pressure may be from ¾ to 2.5 ounces and the volume, per kilowatt loss, may be approximately 150 cubic feet per minute. Readings of all thermometers, voltage, current and air pressure should be taken and recorded throughout the test. The air pressure or volume must be held at a constant value as well as the voltage and current.

When shutting down the test, the air blast and the power should be shut off simultaneously. During the periods of measuring the hot resistance, several sets of readings of the coil thermometers should be taken in rapid succession until decreasing temperatures are indicated. If the coil thermometers indicate higher temperatures after the air blast has been shut off than during the run, it is evident that the temperature indications of the thermometers were influenced by the air blast; therefore, the highest temperature reading must be recorded as the temperature of the winding.

In computing the temperature rise of the windings of the resistance method, the ambient temperature to be used is the means of the chamber air temperature obtained during the last three hours of the test. The standard ambient temperature of reference for air blast transformers is 40 deg. C.; therefore, if the temperature differs from this value, a correction should be made by changing the observable temperature rise in the ratio of the inferred absolute ambient temperature of reference to the inferred absolute temperature of the ingoing air, i.e., in the ratio of $(234.5 + 40)$ to $(234.5 + t)$ where $t$ is the ingoing cooling air temperature.

[5]For the proper method of placing thermometers see the JOURNAL for Jan., 1926, p. 43.



## A Modern Power Plant—In 1892

That was in the days when a switchboard literally was a switch board. The prime movers were the then very efficient, automatic, single-acting steam engines driving 133 cycle generators. Each bearing was lubricated by the drip from a reservoir. It appears that a tin pail to catch the oil overflow was standard equipment with each generator. We can't help wondering if the balcony wasn't used for a visitor's gallery.

A nation-wide search is being made for examples of early electrical equipment of all kinds. If you know of the location of any very old electrical equipment, whether it is still in service or not, will you please notify THE ELECTRIC JOURNAL.

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## Cleaning Commutator Bars

A. C. ROE

IN electrical repair shops it is often necessary to put in new mica segments between bars. In doing this, the old mica and shellac must be removed from the bars, which must be left thoroughly clean. One method is to knock the commutator apart, scrape off the mica against a garnet-paper wheel to remove the shellac and particles of mica adhering to the bars. In nine cases out of ten the wheel removes considerable copper in spots before all the old residue is removed. This method does not make a satisfactory job and, moreover, it takes considerable time.

The following method saves time and shows a decided improvement in the quality of the work. The commutator is knocked apart, i.e., the individual bars are separated by hitting the commutator with a mallet. No attention is paid to the mica adhering to the bars except to gage the thickness of one or two samples, but as each bar is separated from the assembled commutator it is dropped into a wire mesh basket, mica and all. When the whole commutator has been knocked down, the basket is suspended in a tank containing a boiling "Wyandotte" solution and allowed to remain there from three to five hours, depending upon the size of the bars and the number. A tank of any size, such as an old water pail or clothes boiler, will do, provided that the bars are kept away from the bottom. After the boiling, the basket is removed and the contents are emptied onto a flat draining surface, when a stream of clean cold water is turned on the bars, which washes away all particles of mica flakes, leaving the bars clean and bright as new. If desired, instead of turning a hose on the spilled-out bars, place the basket in a pail containing clean cold water and remove one bar at a time, shaking the bar while under water to remove mica flakes. The cleaning process requires very little time and attention and can be done by the average shop helper.

If the commutator bars do not have risers but have a slot cut for the wires, the armature is stripped by chopping off the leads back of the commutator with a cold chisel and the old wire is allowed to remain in the bar until the commutator has been completely remicaed. Then it is put in the miller and the necks milled out.

With the bars that have risers the procedure is to clean in the way already described. The risers should be tinned by dipping in hot solder. After removing the mica, dip the complete bar in clean shellac, place the bar on a mica segment and allow it to dry. Then trim the mica to fit the bar with a knife and a knife file. The bar with the riser is tinned before applying the mica, because with this type of bar the mica does not extend up to the tinned section, hence the part will not get covered with shellac. On the other hand, if the old wires in the low-neck type were cleaned out and the bars dipped in shellac, it would interfere with the soldering.

Dipping the bar instead of painting the shellac on the mica segment has the advantage that, when the commutator is heated for the final setting and tightening, the shellac will soften and cause the mica to adhere to both sides of the bar; also it is a quicker method.

## How to Care for Circuit Breaker Contacts

As far as heating is concerned, the most vital part of a carbon circuit breaker, is the main brush. When in good condition, it should carry rated current at a temperture rise not exceeding 30 deg. C. above ambient temperature. While it is true that overheating may be due to a number of other causes, it is due in a large majority of cases to poor condition of the main brush contacts.

Assuming that the current flowing through the brush is no more than its normal rating, abnormal temperature may be due to:—

1—Insufficient contact pressure.

2—Poor electrical contact between brush and stud head.

For the first case an adjustment is usually provided so that proper contact pressure can readily be obtained. On the second case poor electrical contact may be due either to copper oxide formation on the contact surface or else to failure of some of the brush laminations to touch the stud head. It should not be considered that when a circuit breaker stays closed for a long time that it needs no attention. Oxides form just the same and the circuit breaker should be opened occasionally so that the upper and lower brush contacts and stud heads may be cleaned with fine sandpaper. To determine whether the brush and stud heads are making good contact mark the brush contact surfaces with a soft pencil. Place thin pieces of paper under the brush and then close the circuit-breaker. An imprint on the paper of every lamination of the brush indicates good contact. On the other hand, blank spaces here and there will indicate that some of the laminations are not touching. In this case it will be necessary to refit the brush carefully by filing until it makes good contact.

Overheating may result from the use of insufficient lead capacity or the use of a hot ammeter shunt too near the circuit breaker. Another cause is defective contact between parts of the conducting material other than the main brush contact, such as nuts, clamping terminals; or the bus-bars to the studs may have a poor contact with the studs or with the terminals or bus-bars. This poor contact may be due to insufficient contact pressure, insufficient contact area, or corroded contact surfaces. If the contact pressure is not enough, it is obvious that tightening the nuts after cleaning the contacts, is the remedy.

Insufficient contact area may be due to untrue surfaces on the nuts, studs or bus-bars or terminals, or too small or too few nuts. Contact surfaces that were true when made

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may become untrue by being battered, raising high spots on the surface. When the amount of battering is small and the surface is plain, the best way is to file off the high spots carefully. If the amount of battering is large, it is best to machine the surface. Where the threads on the studs are battered, they can usually be partially restored by filing away the high spots with a small, three-cornered file.

Oxidized and corroded surfaces of threads on studs and nuts may be cleaned by rubbing with a brush, a piece of cloth or waste dipped in a mixture of water and powdered pumice stone, or some other finely grounded scouring material.

Overheating may also be due to a defective soldered joint. It often happens that a soldered joint that was good when made has been partially broken by too great a mechanical load on the joint. The heat then developed has melted the solder causing it to run out of the joint. A soldered joint may be spoiled similarly by an overload, causing the solder to melt and part of it to run out of the joint, rendering it incapable of carrying its rated load.

# How to Select Oil Circuit Breakers

F. B. KNISKERN

NUMEROUS publications go into considerable detail in explaining how to determine the selection of a circuit breaker by calculating the possible short-circuit conditions and by giving full consideration to the maximum service voltage, temporary overload and other typical operating conditions. However, there are many details such as mounting, operation and general characteristics of the particular circuit breakers desired which must not be overlooked. Considerable delay and some misunderstanding may result if one of the seemingly unimportant items is omitted when placing an order or requesting a quotation from a manufacturer. Many orders have been delayed because the frequency of the undervoltage trip attachment was not given, or the loading of the bushing type transformers required in an outdoor circuit breaker was but a guess.

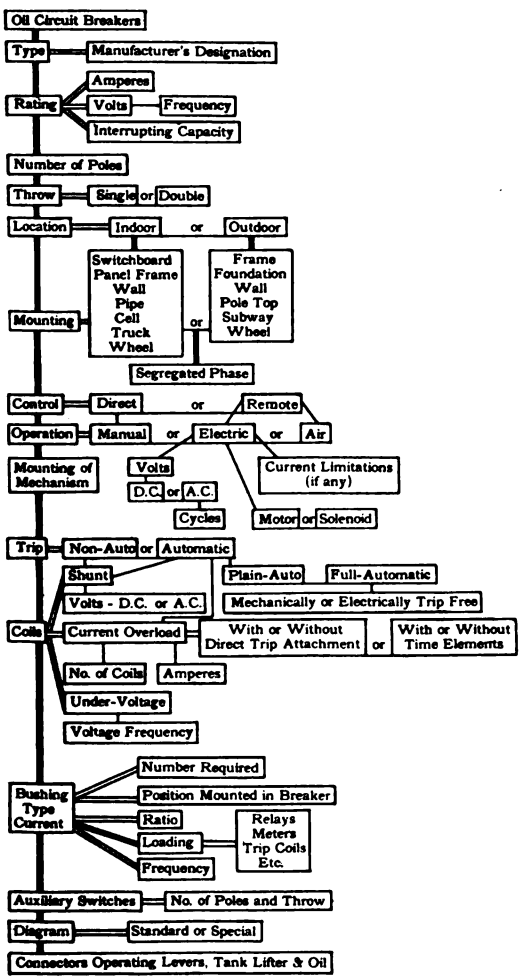


FIG. 1—OIL CIRCUIT BREAKER SELECTION CHART

The information necessary before the oil circuit breaker best suited to a particular need can be selected is given in Fig. 1. The main characteristics appear in the left-hand column with the heavy connecting vertical line. Explanation of these characteristics and secondary characteristics are indicated at the right of the main items. Illustrating the use of the table, suppose we were to consider the trip coil requirements. Shunt trips, overload trips or undervoltage trip coils are possible. The shunt trip coils may be used on either the non-automatic or automatic circuit breaker, but the current overload and undervoltage would only be used with the automatic. In specifying a shunt trip coil it is necessary to give the voltage and frequency on which the coil is to operate. When current overload coils are required, it should be stated whether direct-trip attachments or time-element attachments are required. Thus it is well to trace out to the end of each subdivision to make sure that all necessary information is given when selecting a circuit breaker.

# Treated Fabric and Treated Fabric Tapes

THE question of high quality of insulating materials is of prime importance to all users of electrical apparatus and devices, and particularly is this true of treated fabrics and treated fabric tapes. The varnish used for this class of insulating material should be the highest grade obtainable, and should have several well defined qualities:—

Long life under heat.
High dielectric strength.
High elasticity.
High penetrating quality.

The quality of long life under heat is important, as it insures against early embrittling of the treating material after the apparatus to which it has been applied has been in service.

By elasticity is meant the quality of withstanding distortion of the varnish film without unduly impairing the dielectric strength. The fabric is the mechanical support of the varnish film, and when the treated fabric or treated fabric tape is applied, it is bound to be distorted to some extent. This operation injures the varnish film if it is not specially suited to the purpose.

Penetrating quality is the property of penetrating into the fabric as distinguished from merely coating the surface. A varnish film which is merely a coating will loosen and separate from the fabric when the material is distorted, as when stretched in bias tape. A varnish which is well cemented to the fabric by being soaked into the threads will not loosen readily.

A distinct advantage of thoroughly impregnated material is its superior moisture resisting property. Cotton has an affinity for moisture, and fabric which is well impregnated with varnish has much less capacity to take up moisture and is, therefore, a superior dielectric material to a fabric which has the varnish only as a surface coating.

### METHOD OF TESTS

The test for life under heat is usually made by placing samples of the treated fabric in an oven, heating them to a temperature of 212 to 230 degrees F. for 600 hours and allowing the material to cool. A strip one inch wide cut crosswise of the roll is then tested for life by bending the fabric back upon itself over a mandrel having a diameter of 1/8 foot. The bend should be parallel to the width dimension of

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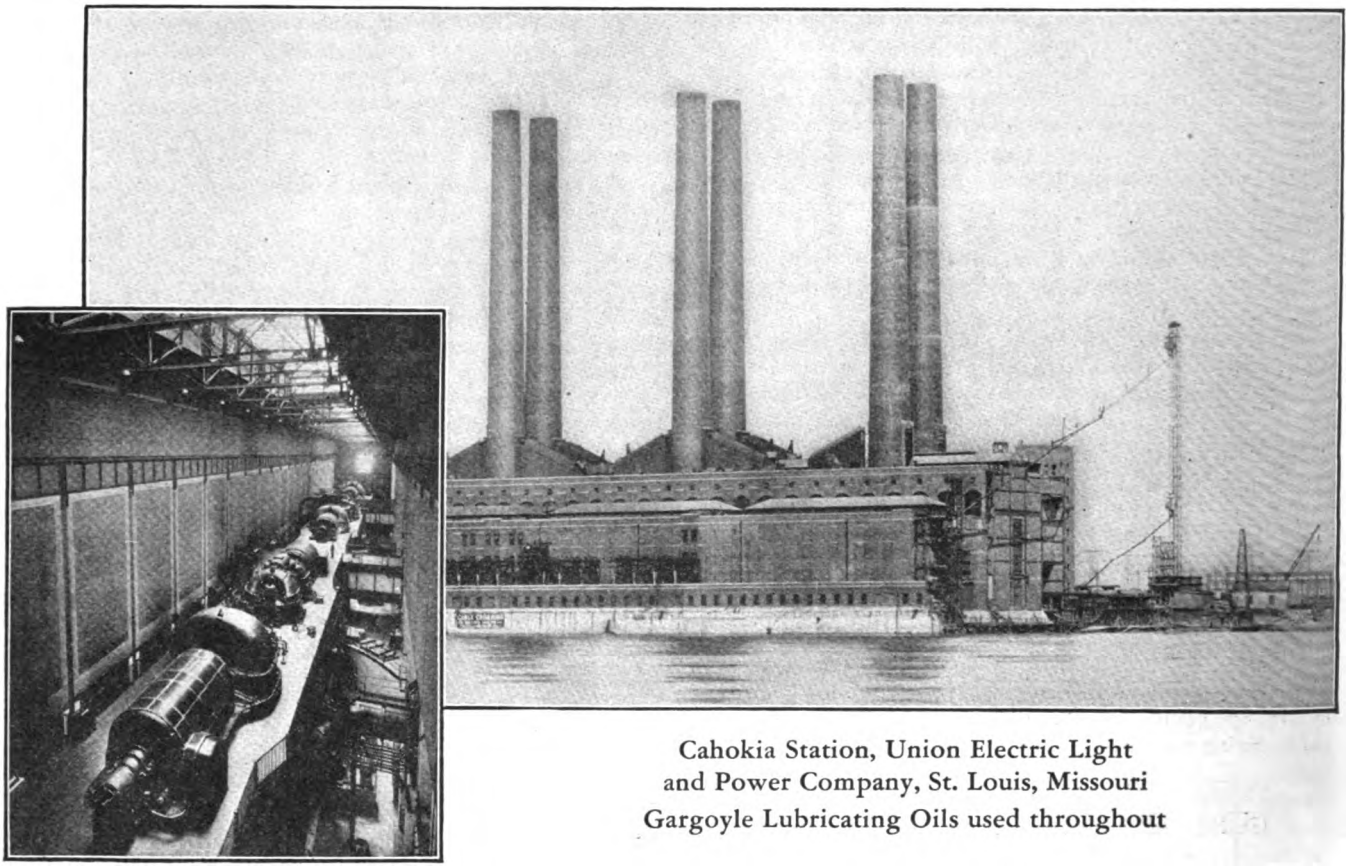

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the strip. The varnish should not crack when subjected to this test.

The dielectric strength of treated fabric is usually measured with the material in the sheet form. The samples must be carefully handled to avoid injury to the varnish film. The terminals should be discs 2 inches in diameter with the edges rounded to a radius of 1/4 inch. In making this test the voltage should be raised at a uniform rate of approximately 500 volts until the cloth is punctured.

The dielectric strength of treated fabric should be not less than 1000 volts per mil in thickness, based on the average of ten tests.

Tensile strength of treated fabric is an indication of the mechanical properties of the fabrics which should be high in order to insure against injury when being applied. The treated material should have a tensile strength of not less than 40 lbs. for the warp threads, and 32 lbs. for the fuller threads, per inch of width.

Tensile strength is usually measured on a machine built for such purpose, which consists of motor-driven jaws which travel away from each other at a slow, uniform rate, with means provided for measuring the pull. The specimens are cut 1 inch wide.

The impregnating quality of the varnish is demonstrated by test for degree of impregnation and adherence of the varnish film to the fabric. In order to bring out this quality a strip of the material is used 3/4 inch wide and 16 inches long on a bias of about 45 degrees. Make a pencil mark near one end and a similar mark 10 inches from the first. Stretch the tape until the distance between the marks is 12 inches and fasten the tape at the ends beyond these marks so that the tape will be maintained in that position. Allow it to remain in this position for 24 hours. The varnish should show no tendency to blister or peel off the fabric at the end of this time.

# The JOURNAL QUESTION BOX

Our subscribers are invited to use this department as a means of securing authentic information on electrical and mechanical subjects. Questions concerning general engineering theory or practice and questions regarding apparatus or materials desired for particular needs will be answered. Specific data regarding design or redesign of individual pieces of apparatus cannot be supplied through this department.

To receive prompt attention a self-addressed, stamped envelop should accompany each query. All data necessary for a complete understanding of the problem should be furnished. A personal reply is mailed to each questioner as soon as the necessary information is available; however, as each question is answered by an expert and checked by at least two others, a reasonable length of time should be allowed before expecting a reply.

2873—PART OF WAVE ON WHICH CIRCUIT BREAKERS OPEN CIRCUIT—The statement is often made that oil-break switches in alternating-current circuits almost invariably open the circuit at the instant when the current is passing through zero value. Please refer me to explanatory literature or tell me why this is true.

S. A. (VA.)

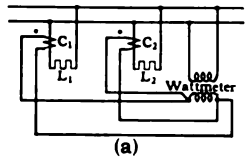
A circuit breaker used for opening a direct-current circuit introduces into that circuit an arc which is elongated until it is extinguished. The equation for a series circuit consisting of a generator of voltage $E$, total resistance $R$, total inductance $X$, an arc voltage $e_a$ and a current $I$ is,—

$$E - RI = e_a + X \times di/dt$$

If the arc voltage $e_a$ is equal to $E - RI$ then $X \times di/dt$, the inductive voltage, must be equal to zero and therefore the current must be constant. In a direct-current circuit breaker this arc voltage is increased so that it is always greater than $(E - RI)$ and so that the inductive voltage, $X \times di/dt$, is always negative. Therefore, $di/dt$ is negative which means that the current must be decreasing. A direct-current circuit breaker forces the current to zero by keeping $e_a$ greater than $E - IR$. The rate at which the current decreases, $di/dt$, is directly proportional to $e_a - (E - IR)$ and inversely proportional to the inductance $X$ of the circuit. A different action takes place in an alternating-current circuit breaker and can be explained by reference to an arc between two stationary electrodes. A high voltage, called the ignition voltage, is required to start such an arc. The magnitude of this voltage depends upon the length of the path and its degree of ionization. After the gap has been broken down and an arc started, the voltage across it decreases to a small fraction of the ignition voltage even though a heavy current is flowing. If the current is now decreased, the arc voltage will rise and, as the current reaches zero, will have a high value, known as the extinction voltage, which approaches the value of the ignition voltage, but is somewhat lower since the path is better ionized due to the more recent arc stream. The extinction voltage may be several times the value of the arc voltage. The ignition voltage is higher because deionization in an arc stream proceeds very rapidly after the current stops flowing. In an oil circuit breaker interrupting an alternating current the extinction of the arc is facilitated by the passage of the current through zero between successive half cycles. At this time, the arc voltage increases as the current approaches zero and the high extinction voltage is reached. The voltage reverses in a very short interval of time but, during this time, the arc path is being rapidly deionized and the voltage required for reigniting the arc is increasing. As the contacts separate, this ignition voltage is increased and at the beginning of some half cycle it exceeds the applied voltage, so the arc cannot restrike and the oil circuit breaker has opened the circuit. The oil circuit breaker therefore interrupts the circuit by drawing an arc, the ignition voltage of which exceeds the voltage applied to restrike the arc after the current passes through zero. The oil assists by cooling the arc, by raising the pressure on the arc and by interposing insulation.

R. C. V.

2874—WATTHOUR METER CONNECTIONS—$C_1$ and $C_2$ in Fig. (a) are current transformers on feeders supplying loads $L_1$ and $L_2$ respectively, from a single-phase line. The secondaries are connected in parallel across the current coil of a wattmeter. Will you please explain why the wattmeter totalizes the load correctly. If $L_1$ is greater than $L_2$ then voltage generated by $C_1$ is greater than that generated by $C_2$. Apparently the impedance of the circuit is too great for




(a)

FIG. 2874

such a small voltage as that generated by the current transformers to cause a circulating current between them, but in the case cited above how does $C_2$ with its lower voltage, supply any of the load to the wattmeter current coil?

J. W. W. (QUEBEC)

The method employing the paralleling of current transformers for totalizing meter indications is simple, accurate and reliable. The loads on the different circuits do not need to be of the same value or of the same power-factor. The transformers must have the same ratio but do not need to be of the same type. As many as six or eight transformers may be paralleled satisfactorily. The current flowing in the secondary of a current transformer depends upon the ratio of the transformer and the magnitude of the primary current and not to any great extent upon the impedance of the secondary burden. The secondary burden usually is a meter coil. If the impedance of the burden should be increased, the voltage generated in the transformer winding automatically rises to a sufficient value to force the current through the coil. The secondary current must flow regardless of the impedance of the burden and if the secondary should be opened causing the secondary current to stop the voltage

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would possibly rise to a dangerous value. When current is flowing through the primary, the transformer does everything possible to maintain its secondary current. If the secondaries of two transformers are paralleled through the same meter coil, both currents must flow through the coil as there is no other place for them to flow, the resultant current in the coil being the vector sum of the two secondary currents. The things to keep in mind is that each transformer is going to do all possible to keep its secondary current flowing and if its voltage should be low, it will automatically raise it to prevent the other transformer from circulating current through it. When the two loads do not have the same power-factor, the secondary currents will be out of phase, and during a part of each cycle, current will circulate between the two transformers, but the current going through the meter coil will be the vector sum of the currents in the two secondaries. In case there is a load only on one circuit, there will be no current in the one transformer but the impedance of the secondary of this transformer will be extremely high as compared with the impedance of the meter coil and little current will be circulated through it. C. O.

2875—OPERATION OF BLEEDER-TURBINE DRIVEN GENERATOR—Referring to Fig. (a) a factory power customer requires exhaust steam for process and heating. It has been calculated that a turbogenerator when producing 2500 kw will deliver the amount of steam required for average conditions. Information is requested on the following points, as well as any complications that may occur to you while considering the problem. 1—What methods or devices are available to secure stable operation of one of the turbogenerators when operated in parallel with the power company's ring feeder, at any desired constant load, without continuous manual supervision or manipulation of the turbine governor. The object in

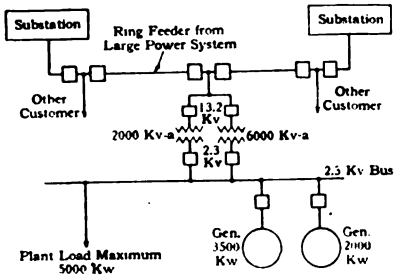


FIG. 2875

view is to pass sufficient steam through the turbine to supply the factory with the required amount of exhaust steam, and the excess, or shortage, of the power produced, over or under that required by the fluctuating plant load, to be fed into, or drawn from, the power company's ring feeder. 2—Can the turbogenerator be operated in parallel with the power company's ring feeder at any desired power-factor, and what scheme of voltage control would be most satisfactory for this purpose. What effect will changes of power-factor on the power company's ring feeder or in the plant load have on the turbogenerator? Would a generator voltage regulator with the current winding on the alternating-current magnet energized by a current transformer connected in quadrature to the potential winding be of assistance in maintaining a desirable power-factor? 3—What scheme of protection should be used to protect the generator and transformers, as well as the electrical machinery in the factory, in the event of the power company's ring feeder becoming disconnected from both substations, and then reconnected without notice?

R. J. (N. J.)

1—(a) The first sentence speaks of a machine to satisfy process steam demands and to maintain "any desired constant load". We presume that this means constant electrical load. This refers to either an autobleeder or a combination of non-condensing and condensing unit. Assuming a bleeder, the use of a compensator device will serve closely to maintain constant electrical load with changes in bleeder demand, that is; division of load between the system and the turbine will not be much changed as the bleeder demand changes. Or, there are electrical devices available to operate back on the turbine speed changer to keep the load generated by this machine within narrow limits. Having variable bleeder demand and demanding practically constant generated power obviously requires a section of the prime mover available to develop variable load and this is furnished by the condensing end of an autobleeder. (b) The second sentence covers a non-condensing machine with exhaust pressure regulator. This device will cause the turbine to pass whatever steam is required to maintain the desired process pressure and to deliver whatever power may be obtainable from the expansion of this steam from throttle to exhaust pressure. In this case the power obtained will change as the exhaust steam demand changes, the incoming power supplying any deficiency or absorbing any excess. This machine will not respond to changes in electrical load. 2—The voltage on the bus will be fixed by the large system. The 2500 kw turbo-generator will probably not influence it very much. The field rheostat of the generator should be set to give the desired power-factor at full-load and left there. At smaller loads the generator will feed wattless kv-a into the system, but this cannot harm either the system nor the generator. However, if reasons exist why such operation is not possible, power-factor regulators working on the principle stated are available. 3—A relay must be provided to open the tie-breakers if the supply from the power system fails. When voltage has been restored on the power system, it will be necessary to synchronize the turbo-unit with the power system in the usual manner. No other protection against failure of the supply from the power system will be required.

J. D. S. AND C. A. P.

2876—SYNCHRONOUS CONVERTER OPERATION—Is it possible to start and operate a 200 kw, six-phase, 60 cycle synchronous converter double-delta connected with one of the transformers

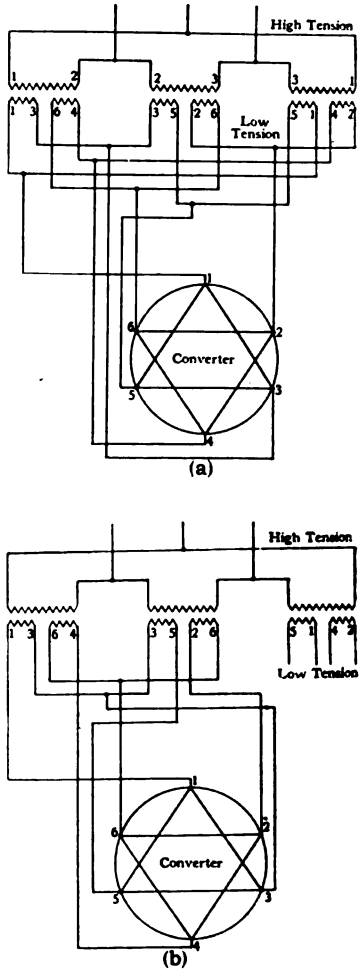


FIG. 2876

cut out? In event this can be done please show connections.

G. G. D. (W. VA.)

It is possible to start and operate a six-phase synchronous converter when double delta transformer connection is used, even though one of the transformers be omitted. In operating a converter under such conditions, however, the load should be reduced to about 65 percent of normal, in order that overheating of the windings from the unbalanced current is not obtained. The normal connection for a standard double-delta-arranged converter is given in Fig. (a). Also, the connections obtained when one of the transformers is omitted is shown in Fig. (b).

R. H. N

## CORRECTION

In the August 1928 issue, p. 408, in the third line under Fig. 41, the word "square" should be "cube".

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# THE ELECTRIC JOURNAL

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**Air Ejector Selection for Surface Condenser Installations**

An inspection of the proposals for condensers for any particular installation often reveals wide discrepancies in the air handling capacities and steam consumption of the air ejectors offered with the condensers. Comparatively few operators issue complete specifications on this particular point, and there is a wide variation in the practice of the different condenser builders in applying air ejectors to condenser installations.

This results in considerable confusion and misinterpretation by the operators of the guarantees made by the different builders. One manufacturer may apply ejector equipment which will have sufficient air handling capacity only when the air leakage is kept down to low limits, while another may apply equipment having liberal capacity. The purchaser, as a rule, merely compares the steam consumption, assuming in each case that the builder has applied a size which will permit the condensing apparatus to function in accordance with the specifications.

Such a situation penalizes the manufacturer who supplies an ejector of liberal capacity, while in reality it would be beneficial to the purchaser to have this liberal capacity furnished. Also, the ejector equipment which is of sufficient capacity only as long as the air leakage is kept to a minimum, may have been provided for some certain specified condenser performance. It may be found to be of too small capacity when the turbine is operated at light loads, which results in higher vacuum and at times increased air leakage due to more of the turbine casing being under vacuum. It is suggested that definite allowable air leakage factors be established, expressed as pounds per hour of 70 degrees free dry air leaking into the condenser. Curves can be made showing the weight of dry air handling capacity to be provided for, plotted against the weight of steam condensed.

In determining these air leakage factors, consideration should be given to the various types of turbines served by the condensers, the air handling capacity required bearing a relation to the number of low-pressure elements and the number of glands exposed to vacuum. Also consideration should be given to the arrangement of feed water heaters with respect to whether separate air removal equipment is provided for removing the air from the heaters, or whether they are vented back to the turbine casing, or successively into the next lower pressure heater, and thence to the condenser.

There are many installations today where the turbine is penalized by insufficient air handling capacity at the lower absolute pressures. The highest vacuum at which the turbine will normally be operated should be considered when the ejectors are selected. It is possible to design an ejector so that it will have a higher capacity at the lower absolute pressures by sacrificing capacity at the higher absolute pressures, without increasing the steam consumption. Therefore, not only the steam consumption of the ejectors should be considered, but their capacity at the normal operating vacuum.

The operator is interested in the vacuum realized at the top of the condenser, and if the air leakage is specified at a given absolute pressure, the builder must take into account two factors:—the pressure drop through the condenser and the vapor volume, which depends on the temperature and pressure of the mixture at the air offtake. This would penalize condensers defective in design and be an incentive to build condensers having a minimum pressure, and maximum cooling effect on the vapors to be removed from the condenser.

A movement, sponsored by some authoritative source, to establish definite allowable air leakage factors would be productive of mutual benefit to the operator and to the builder.

C. B. TULEY

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**Standardization of Electrical Measuring Instruments**

One of the outstanding features of the modern industrial system is standardization. According to figures recently made public by officials in Washington, about $300 000 000 is being saved annually through simplification of practices and standardizations that have been worked out in recent years.

The need for eliminating the waste resulting from excessive varieties was emphasized in 1921 when Secretary of Commerce Hoover, acting for an engineering organization, appointed a committee which made surveys of waste in various industries. Then the Department of Commerce established its Division of Simplified Practice, which, working with the industries, effected very important reductions in the total number of types of manufactured articles. National engineering societies and many trade associations have long carried on a program of standardization which has been of enormous benefit to industry in savings and in simplification of their products.

Previous to the organization of the Division of Simplified Practice and as a war measure, the Navy Department and the principal instrument manufac-

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turers recognized the need for simplification of types and standardization of instruments. Working jointly on this basis, a specification for switchboard indicating instruments was built up and adopted, standardizing on four sizes of switchboard instruments. These were all of the round type and were 2 9/16 in., 3½ in., 4⅜ in., and 7½ in. in diameter.

As an illustration of the adequacy of these standard sizes, one of the principal instrument manufacturers has found that the four classes of instruments enumerated above have been sufficient to meet every possible operating condition which has presented itself during the last ten years. There have, of course, been occasional demands for variations from this program, such as grouping three small ammeter movements in one larger instrument case of the 7½ in. diameter size; but this used standard parts of the small and the large instruments, and is in the nature of "special apparatus", nothing being gained in either space, performance or cost as compared to the use of three separate small ammeters.

Another notable variation from this proposed standardization has been the square case line of switchboard instruments more recently brought out by several manufacturers, primarily to fit a tendency to standardize switchboard panel widths on the basis of a six inch horizontal spacing arrangement per circuit. The square instrument allowed a scale length equal to that in the 7½ in. round type instrument. This same problem was solved by another manufacturer by retaining the standardized round-type construction, as in the 7½ in., but providing a case which reduced the marginal waste spaces resulting in a case only 5½ in. wide with the scale length of the previous 7½ in. type.

There certainly does not seem to be much need for so many kinds, beginning with the 4⅜ in. size and ending with the 7½ in. size and including both the square and the round 5½ in.-6 in. forms. Nor does there seem to be much need for both flush and projecting (front of board) mountings in each size. The 2 9/16 and the 3½ in. sizes might well be standardized for flush mounting only and the larger sizes for projecting mounting only.

Before this specification was adopted, there were numerous varieties among the different manufacturers of the country, such as vertical edgewise, horizontal edgewise, fan shaped and round types of many diameters, resulting in divided production effort, increased complications and costs, as well as in the Navy Department's specific difficulty of not being able to carry stocks of spare instruments which would fit panels originally drilled for some specific make.

The important American instrument manufacturers have now produced more or less complete lines of instruments, both alternating current and direct current, in these four basic sizes, and some manufacturers are confining their developments to these sizes only, wherever they find it possible.

It is thought that in the course of time this war period attempt at standardization will be accepted as a general industry standardization with resulting benefits to users as well as manufacturers. P. MacGahan

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**Balancing in the Field**

The balancing of the rotating parts of machinery to avoid vibration has been important as long as there have been machines. With slow-speed machines or those of short axial length, a static balance was sufficient for practical purposes.

However, rotating machinery is both speeding up and getting larger. In a long machine it is possible to obtain static balance and still have an unbalance at one end with an equal unbalance on the other side at the other end. Such a rotor at high speed would tend to run on its own true axis of rotation rather than on the geometric axis. This sets up a vibration at the bearings which is most disturbing both to the bearings and to the nerves of those in the neighborhood.

True dynamic or running balance began to be important with the introduction of large high-speed machinery. This problem was first solved by the trial and error method with a certain amount of assistance from a piece of chalk, which gave a general idea of the location but not the amount of the unbalance. Some few persons developed a knack at such balancing but even for them a running balance was uncertain and troublesome to obtain.

The result of careful study of this general problem, which is by no means limited to electrical machinery, was the dynamic balancing machine. These instruments will determine with a high degree of accuracy the size and location of balance weights necessary for a running balance of a vacuum-cleaner motor or of the largest turbines and turbine generators.

While the balancing machine is very useful in a factory, it can scarcely be considered a portable device. Balancing in the field has, therefore, been necessarily done by the older methods.

Balancing in the field, however, has been greatly simplified by a new method, described by Mr. Ryan in this issue of the JOURNAL. By a most ingenious application of force vectors, he has bodily transferred all the trial balancing from the turbogenerator floor to the drafting table; substituting, therefor, five successive runs under different but known conditions. The new method is still a trial method; i.e. the location of a point on a sheet of paper is determined by trial from the observed data, each trial giving an indication of where the next one should be made. From the resultant vectors, the exact position and amount of the final balance weights are determined. Obviously, this is much simpler than it is to make a much larger number of trials on a heavy rotating mass, which must be brought up to speed and stopped again for each trial.

CHAS. R. RIKER

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# Standard Line of Direct-Current Machines Fabricated by Arc Welding*

R. S. MARTHENS
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C. C. BRINTON
Manufacturing Engineer,

F. T. HAGUE
Design Engineer,

Westinghouse Electric & Mfg. Co.

AN existing line of direct-current machines using castings cannot be changed over to the arc welded fabricated construction simply by replacing castings with similar fabricated constructions, without sacrificing many of the attractive possibilities which the new method of construction makes possible. A particularly valuable feature of fabricated construction in direct-current machines of medium and large size is the design flexibility of the arc welded construction that permits a wide application of any given element of the machine. This feature alone has an economic aspect which justifies the complete redesign of the entire line of machines to take full advantage of all the opportunities of flexibility in design which the arc-welded fabricated construction alone makes possible.

**Direct-current machines have not been the first to be completely fabricated by electric arc welding. Electrical manufacturers have generally followed through the development of simpler types of alternating-current synchronous machines, accumulating experience in fabrication and developing correct welding technique as applied to electrical structures, before undertaking the fabrication of the direct-current machine. Under these circumstances, the completely fabricated direct-current machine can reasonably be expected to benefit from this previously accumulated manufacturing experience.**

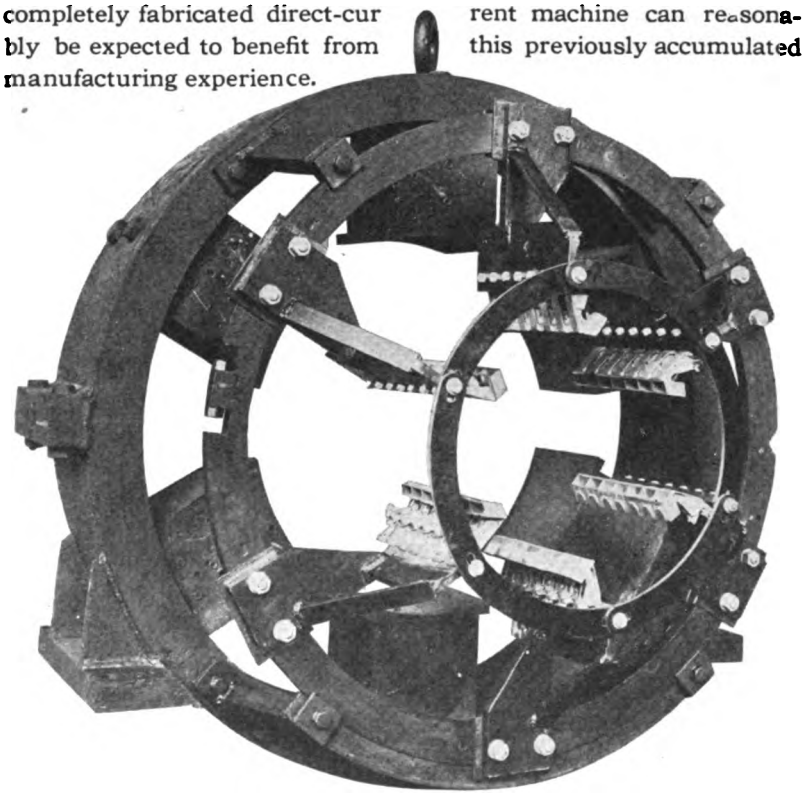

FIG. 1—A TYPICAL, CASTINGLESS DIRECT-CURRENT STATOR. THE ENTIRE FRAME AND BRUSH RIGGING ARE MADE FROM ROLLED STEEL SHAPES, CUT BY GAS FLAME AND ASSEMBLED BY ARC WELDING

The direct-current machine is essentially one for specialized applications, and as a result, individual types of construction using castings have been developed for mill, hoist, marine, and engine-driven applications. Individual lines of electrical rating have been developed for each type of service, but continual development in these industries and application changes have effectively prevented extended duplication of specific ratings; nor is it probable that these conditions will be materially changed in the near future. The present demand is for special electrical ratings and constructions, and this must be met with low cost apparatus, unburdened by high development charges. The arc-welded fabricated construction makes possible the necessary flexibility in design to meet these requirements.

It is not proposed to fabricate the largest or smallest sizes of direct-current machines at this time. Lying between the class of special large machines that must be built to order, and the standardized small industrial product built for stock, is a large and important class of machines of medium-size that constitute a particularly difficult design and production problem. They cannot be built for stock because of the wide variety of designs required; and they are too small to absorb the high special development and labor costs incidental to special design and custom building. For this class of product, it is proposed to adopt a novel method of design and manufacture, particularly adapted to fabricated construction, that will combine the flexibility possessed by the special built-to-order system and the low cost of the standardized built-for-stock system.

The importance of the manufacturing problem rising from this medium-size class of direct-current machinery is increasing rather than decreasing. The percentage of special machines is still steadily increasing, owing to the outstanding advantages of electric drive and its adaptability to all sorts of mechanical conditions and requirements. This tendency may be re-

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gretted by the machine designer, but wisdom requires that ways be found of meeting this condition with as little sacrifice in manufacturing economy as possible.

The development of the arc-welded fabricated construction has made it possible to combine these contrary requirements of design flexibility and low manufacturing cost by the application of the standard-part idea to electrical-machine design. Basically, the standard-part plan means the separation of a direct-current machine into parts or elements, some of which can be used in many different designs and others which will generally change with every design. The major mechanical elements, such as frames, armature spiders and punching blanks, are obviously parts which can be standardized. Windings in general are variable elements that change with each rating.

The purpose of this plan is to reduce the standard parts to a minimum number of sizes and so to organize the method of design of complete machines that a given standard part will be used throughout the entire range of rating within the scope of this line of machines. The fabricated construction alone makes this plan feasible without incurring prohibitive development charges for patterns, etc. There is nothing new in the standard-part idea itself; the new element is the application of this old idea to the fabricated construction of the internal parts in complicated direct-current electrical machinery, in such a way as to meet exact performance requirements.

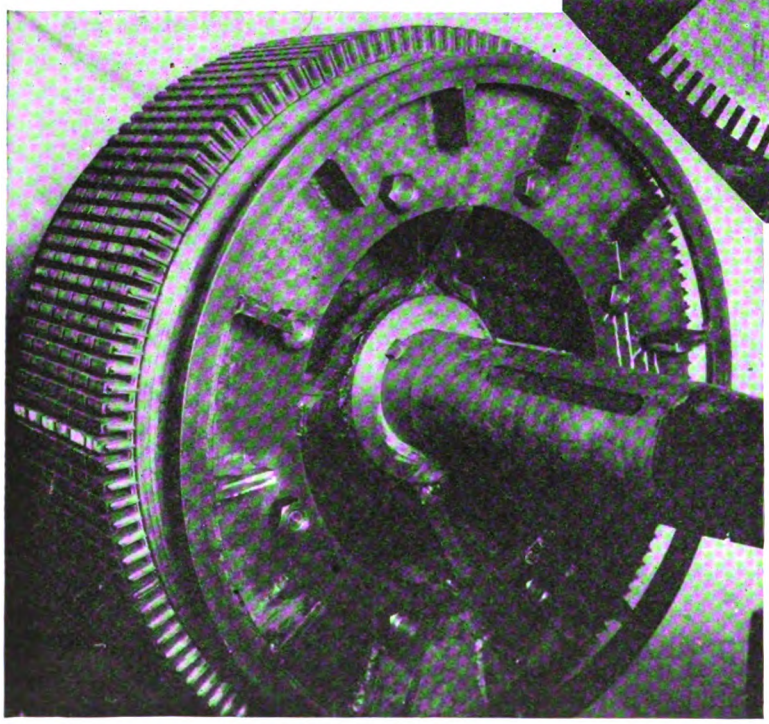

FIG. 2—A COMPLETELY FABRICATED DIRECT-CURRENT ROTOR

Successful application of this idea requires a complete change in the designer's objective and method in designing the entire line of machines. The unit of design is no longer a single rating with the problem of making the best possible special design for that rating alone. The new unit is a single part—a frame, main pole, armature punching, commutator, etc.

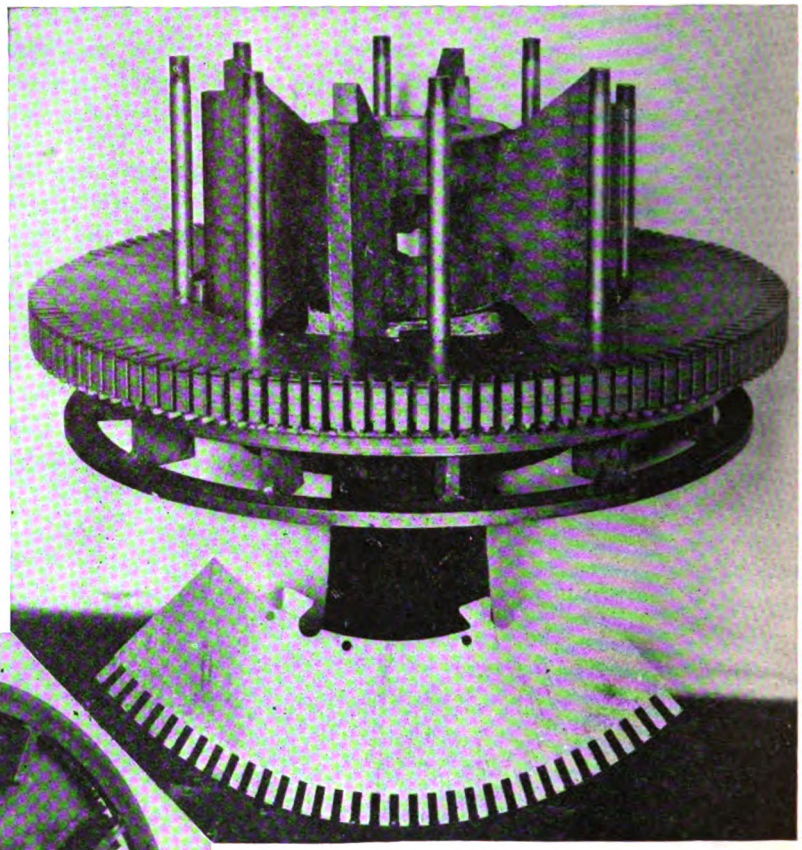

FIG. 3—FRAME FOR MOUNTING THE LAMINATIONS ON THE FABRICATED SPIDER

The problem is to design that part so that the desired range of ratings can be built satisfactorily with competitive performance, with the minimum number of sizes of that part, and to design the individual part so that it will have a rational application when assembled into completed machines. Some parts of the machine will necessarily vary with every rating, but these parts are essentially electrical and are not important from the standpoint of welding applications. The essence of the standard part plan of fabricated construction is to simplify the design of the product so that mass production technique can be applied, as it is recognized that low manufacturing costs result from standardization and mass production. It has been pointed out that in the direct-current machinery business there is not a sufficiently large volume in number of units to be concerned with mass production methods. The real significance of mass production, however, is not so much the quantity of production as it is the simplification of the product. The important concept is not so much large

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quantity as it is small variety of design.

The standard part plan of fabricated construction greatly simplifies the welding problems by reducing the variety of welds to a small number of standard types. For each of the relatively small number of standard parts, a master design is created and each element manufactured is identical in design, and differs only in physical dimensions. The manufacturing problem, and the welding technique required can obviously be given the utmost consideration in view of the limited number of such parts involved. For example, it has been found possible, with but one exception, to design the entire line of standard parts using only four sizes of simple fillet welds. Skill in design rather than brute strength in welding, has been called upon to avoid complicated welded structures that the timid or ultra-conservative engineer might consider questionable at the present time.

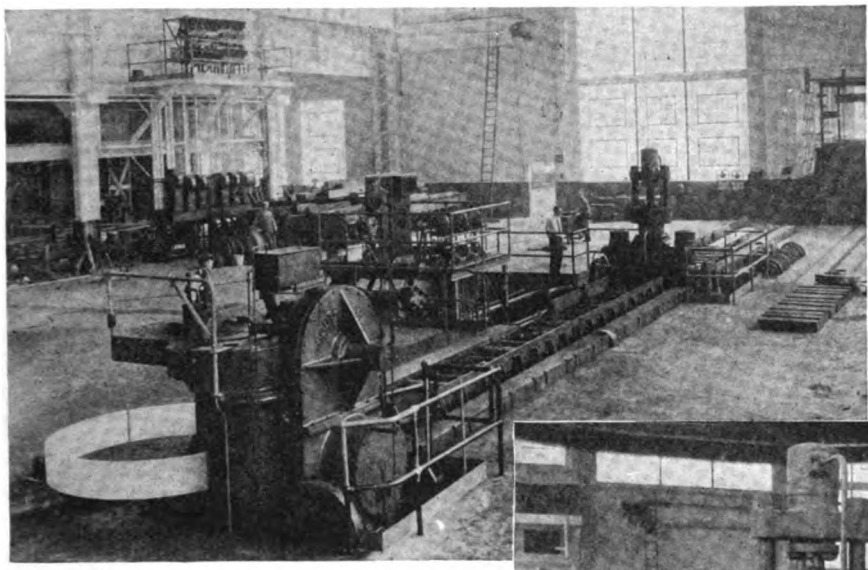

FIG. 4—THE NEW MILL FOR FABRICATING DIRECT-CURRENT MOTOR AND GENERATOR FRAMES FROM STRUCTURAL PARTS

The steel is placed on the furnace table and is heated in the furnace at the extreme right. The table is then drawn out by the motor-driven chain in front of the furnace and the steel is lifted to the rolls in front of the crimper. After passing through the crimper the steel goes to the vertical bender and is rolled to the desired circular dimension. The frame is then ready for the arc welders.

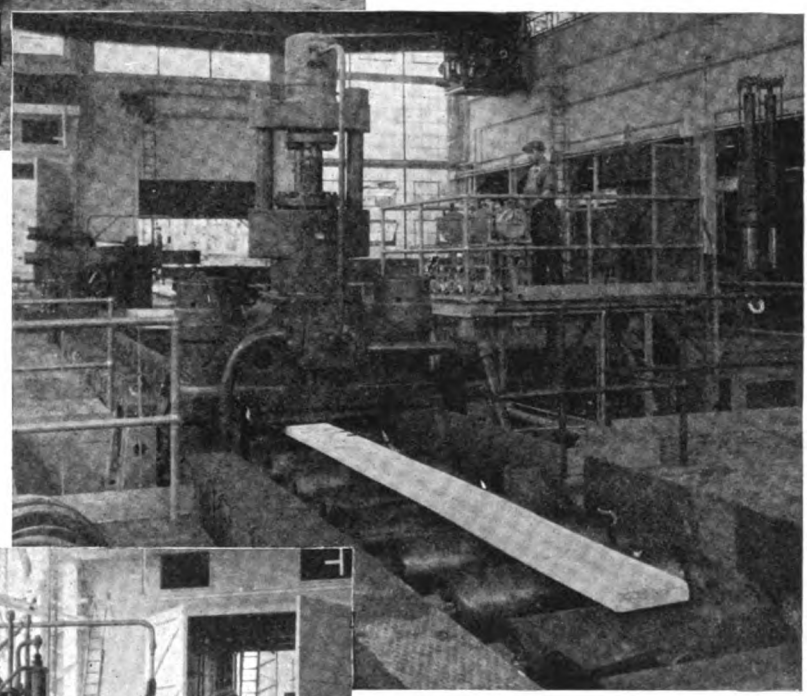

FIG. 5—THE HYDRAULIC CRIMPING MACHINE

The slab on the motor-driven roll table in the foreground is about to have its ends given their initial bend preparatory to going to the bender. The pulpit from which the furnace car, roll tables, crimper and bender are controlled is immediately to the right of the crimper.

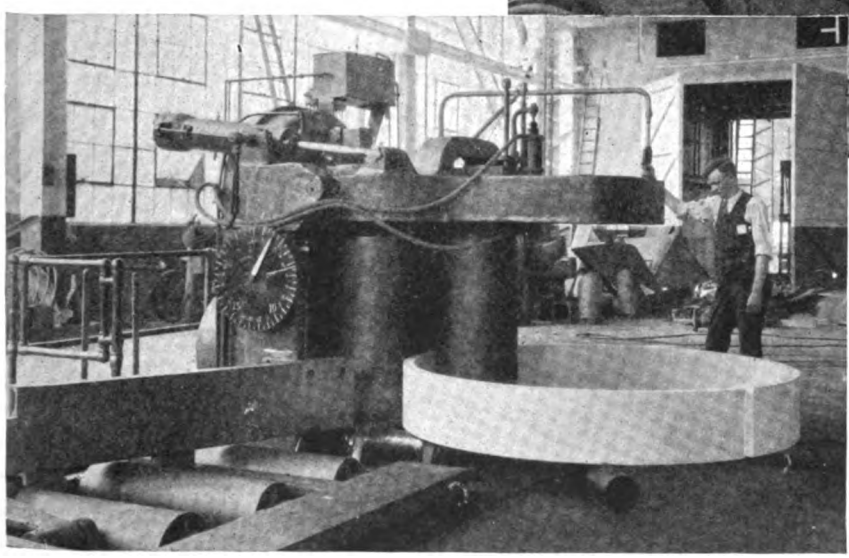

FIG. 6—THE THREE-ROLL VERTICAL BENDER

Although the direction of rotation of the rolls is controlled by the operator in the main pulpit, the speed can be controlled at the bender by the switch in the operator's hand. The overhead mounting of the roll inside the frame is pivoted, as can be seen above and a little to the right of the screw-down dial. To remove a frame after it has been rolled, the roll and its mounting are swung upwards by the hydraulic piston at the top.

The following general principles were adhered to in the development of the larger sizes of this line of completely fabricated direct-current machines. In analyzing these principles it must be kept in mind that the application of arc welding to the rotating members of direct-current machines is relatively new, and that

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ultra-conservativeness in the welding application is considered desirable at the present stage of the development.

The mechanical safety of the rotating armature member must not be dependent upon the security of any welding. This favors the use of through bolts to hold the armature core and commutator together, and the use of rolled steel V rings.

The centrifugal forces of the rotating armature core and winding must not be carried by any welded joints. The armature core is built up of laminated segmental punchings so interlocked by steel pins that the entire unit is a self-supporting ring merely centered and driven by the fabricated spider.

Unyielding elements which are rigidly held apart and are unable to approach each other slightly when the welding metal cools, should not be joined together by welding. As an example, armature spider arms are not welded to both the unyielding hub rings and the armature core element. They are welded to the hub ring only and are attached to the core through a simple mechanical press-fit connection. Avoiding difficult welded structures eliminates the necessity of annealing parts after welding.

Electric current is not carried through any welded steel joints in the brush rig construction owing to the uncertainty of the resistance of welds in paralleled electric circuits.

Simple fillet welds of small size should be used. Welds of large cross-section are less desirable in that they require a large amount of welded metal per unit of strength, and are less readily inspected than small welds. Being built up in successive layers, the large weld is rather more subject to unequal stress distribution due to temperature effects during cooling.

Stresses in welds must be ultra conservative, even under the condition of short-circuit on the machine. The value of short-circuit torque has been determined and a large factor of safety has been used in the application of the welds. On the rotating part, the welds must be stronger than the steel pieces joined together.

The shape of the replaced casting need not be maintained in creating the new fabricated element. Very often it is found that an efficient design for fabrication takes a shape entirely different from that of the obsolete casting, and the new shape can be made more nearly the ideal for strength.

A small number of stock-size bars, sheets, slabs and structural shapes should cover the entire line of design. Proper planning in this respect is required to maintain a minimum scrap ratio and will be repaid by low costs.

The designs must be so made in conjunction with the manufacturing engineers that proper allowances and tolerances will be made for mill variations in the dimensions and flatness of steel shapes, the unevenness of burning, and the distortion due to welding. The sequence of manufacturing operations which will give low cost very often calls for new ideas. With fabricated steel parts, it is frequently possible to omit entirely certain machining previously required in the use of castings. The designer must keep in close contact with the manufacturing engineer, as many new developments may thereby be applied to parts other than the one which led to their inception.

The control of the design of shop tools and fixtures is an integral part of the design of the machines themselves. The problem of tools and fixtures is more difficult with fabricated steel parts than with castings, one of the reasons being the greater flexibility inherent in the fabricated designs. It is essential that this flexibility should not be restricted too greatly by shop tools and fixtures, and it is frequently a problem whether to provide a universal fixture, or one applying only to a particular size.

The fabrication of a line of machines requires considerable special factory layout and equipment. The full advantages available from the arc-welded construction can only be realized by courageous scrapping of existing manufacturing equipment, and the installation of new equipment of novel type. In place of the foundry, there will be substituted furnaces and bending rolls for the rings used in the direct-current frames. In place of the machine tools, there will be automatic gas-cutting machines, and finally, automatic welders, etc., required for fabricating. Thus, there are heavy initial development costs that must be incurred before manufacturing can begin.

The factory layout for the manufacture of direct-current machines is to some extent merged with other lines of a similar character. It is a more simple problem for the manufacturing engineer to make an efficient and economical layout to manufacture fabricated machines than it has been in the past when castings were used throughout. The storage of the required stock of parts, the handling of these parts, and the performance of various operations, has been worked out to suit the new material used. This has, of course, required a complete re-arrangement of the existing manufacturing layout.

The manufacture of the various parts is laid out so that the cutting, cleaning by shot blast preparatory to welding, and the welding itself, is completed with a minimum of handling. Frame rings are bent, cleaned, and accessories welded on in the same shop section by a single group. The rotating parts, however, are handled by a separate group on account of the higher grade of workmanship required. The small variety of types of designs has been found to facilitate good welding. The welders of this group are selected from those who have received training in the welding school and have shown special aptitude in regular production work of less importance. The supervisors and inspectors are chosen with a view to securing good welding and reliable inspection of the welding process, as well as the finished product.

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Special equipment is essential to produce the parts for direct-current machines, such as that developed for the manufacture of heavy frame rings. The equipment for making these rings includes a furnace for heating the heavier slabs for bending. It is desirable to heat slabs of more than 3½ in. thickness before they can be formed into rings. A set of motor-driven roll tables with hydraulic turn-over apparatus, handles these slabs from one operation to the other. A crimping press and a vertical three-roll bender completes the equipment for the manufacture of the rings. The crimper is a 1000 ton hydraulic press equipped with dies for bending the slab ends before they go through the bender. This makes it unnecessary to cut off or bend by hand the straight ends left when such rings are bent in a three-roll bender. It is unnecessary to provide a die for each diameter as one die can take in a range of diameters by proper manipulation of the press. The press thick and 12 in. wide to 60 in. minimum diameter. The controls are centralized at a pulpit placed so that the furnace door and car, roll tables, crimper and bender may be under the control of one man who can oversee all of the operations.

The welding fixtures are all made from structural shapes and are completely welded together, taking advantage of the adaptability of this material for such parts. The fixtures have been designed with particular attention to securing the best arrangement for assembling the parts and for ease of welding. These welding fixtures, wherever possible, are made so that only one fixture is required for each part of the line, regardless of its size. This feature has been secured with no sacrifice of the adaptability of the part or undue complication of the fixture. In order to take the greatest advantage of the possibilities inherent in this type of construction, it is necessary to allow much less

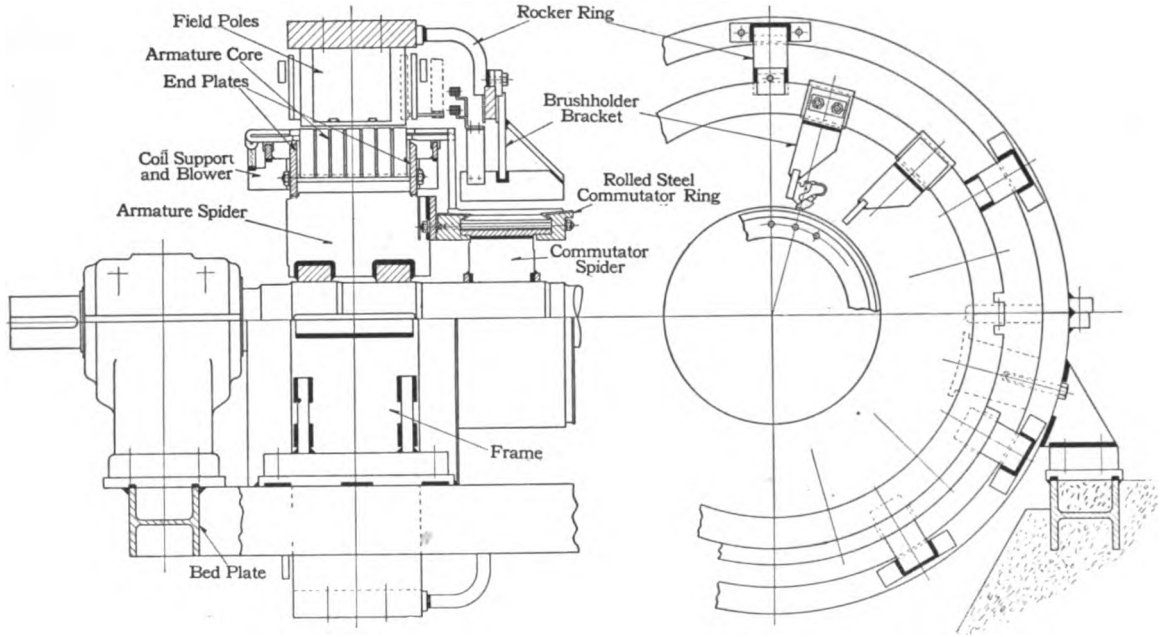


FIG. 7.—A TYPICAL, FABRICATED DIRECT-CURRENT MACHINE ASSEMBLY

is supported on roller trunnions so that it can spring with the piece being bent, thus allowing the rest of the piece to be flat on the roll table. After crimping both ends, the roll table carries the piece to the "pick-up", which turns the slabs on edge ready to be entered in the bender.

The bender is a vertical three-roll machine with motor-operated rolls and an individual motor-operated screw-down. The screw-down is made heavy enough to bend the piece by centering the slab and operating the screw-down motor. This makes it possible to begin the bending operation from the center of the piece if desirable, or to bend without allowing it to pass out of the rolls. Guide rolls are used to support the free ends of the rings to prevent possible distortion while bending. The bender is capable of handling a slab 36 in. wide and 3.5 in. thick without heating. The smallest diameter ring that can be made is 30 in. with no limit to the maximum. It will also edge-bend rings 2.5 in. stock for machining than has been needed for castings. To accomplish this result, adequate welding fixtures must be provided so that the parts are held in proper relation to each other and the welding done in a way to produce a minimum distortion of the finished parts.

The raw material necessary to manufacture both the rotor and stator is carried in stock either in mill lengths or multiple lengths for that part for which it is to be used. The investment needed for a complete stock of this kind is small compared with that which would be needed to carry an equivalent stock of castings. It is quite probable that the investment and the handling of a complete stock of castings for such a line of machines would be prohibitive under any manufacturing conditions.

In the following, the details of a few of the major parts will be made clear by referring to the sectional view of a typical machine, shown in Fig. 7.

The magnet frame is made up of steel bars and

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slabs joined together by arc welding. All welds are located on the outside and are of the simple fillet type. The frame foot welding must withstand the stresses due to electrical short-circuits of the machine and these welds have been calculated to have an ample factor of safety under this condition. The welding at the split of the frame and the lifting lugs is determined by the weight of the parts, and the permissible deflection of the frame, rather than by load torque conditions. These welds have been calculated to withstand the stresses due to handling in the factory, and installation of the assembled stator. The number of bar and slab stock sizes required for a line of frames accommodating armatures from 25 in. to 100 in. in diameter, is surprisingly small. For 30 frame sizes, only 5 bar sections are required for frame feet, 5 sections for foot ribs, and 6 sections for lugs at the frame split. The shop welding fixture for these frames is a universal

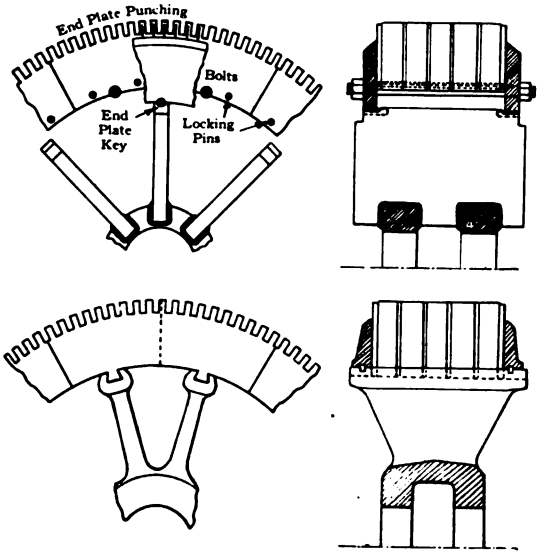


FIG. 8—THE NEW AND OLD STYLE PUNCHING AND SPIDER DESIGNS
In the fabricated construction (above) the punchings are built on bolts. In the cast construction (below) they are built on dovetails.

fixture capable of being used with all diameter armatures between 25 and 100 inches. In this welding fixture provision has been made for locating the frame feet at any desired height as required by the machine installation.

A desirable saving is made in development by the elimination of the patterns and the continuous changing of patterns to obtain the foot height required in different installations. Delivery time is also reduced as a natural result of fabrication, in that there is no pattern to make or remove from storage, no likelihood of scrapping castings and the machining time for the fabricated frame is considerably less than that of the cast frame.

The brush rigging is of the heavy-duty rocker ring and brushholder bracket type and is completely fabricated, all pieces being held together by arc welding. It is believed that fabricated steel parts have a greater tendency to vibrate than do cast parts and this has been recognized in the layout of the new structure. Various samples have been built and their comparative rigidity tested. The final design is a rugged rigging more capable of standing severe service than the replaced cast design.

All welds are of the outside fillet type, the parts being so arranged that electric current does not pass through any of the welds. The rigging is made in halves, being bolted together to facilitate installation and dismantling in case of repairs to the machine. The rigging is also capable of being readily shifted to obtain the correct electrical neutral position.

The brushholder brackets are made of two steel bars joined at right angles by arc welding, the horizontal bar being notched to receive the vertical bar. Rigidity is obtained by a brace between the outer end of the horizontal bar and the vertical bar.

The shop tools and fixtures for the brush rigging include a fixture for holding the rocker ring supporting arms in position while welding the blocks at either end, a planing fixture for these arms, a drill jig for one pair of brushholder brackets, a welding fixture for the brushholder bracket members, a machining fixture to assure true faces as required on these brackets, and a drill jig for the brushholder bolt holes. For the brushholder brackets of the 30 machine sizes only two bar sections are used for the horizontal members and two sections for the vertical members, with two sections for braces. Three standard channels are used for the brushholder supporting arms and three bar sections are used for the shift rings to which the brushholder brackets are attached.

The armature spider, Figs. 2 and 3, is composed of two hub rings and the necessary arms, both burned from steel plates. The spider arms are notched by gas cutting to receive the hub rings. The end plates, as well as the commutator supporting ring, are also burned from steel plates. As previously noted, certain definite principles have been adhered to in the design of the rotating welded members and much thought has been given to the type of welding used in joining the hub rings and the arms together. With the arms notched to receive the hub rings, ample welding can be applied to obtain conservative weld stresses under the most strenuous operating conditions.

The armature spider construction is, of course, dependent on the method used to build up the armature core. In this line of machines the armature core is built up on bolts which extend through both end plates and maintain pressure on the laminated core. The core and end plates, as shown in Fig. 8, are self-supporting as far as centrifugal forces are concerned, and the spider serves only to center them and transmit the torque to the center of the machine. The connection between the end plates and the spider arms is made by a shrink fit and fitted dowels. The commutator supporting ring is burned from a plate and is welded to the end of the spider arms. These welds are capable of withstanding the pressing-on of the shaft of the

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completed rotor, as is required in some engine type applications.

The only stress in welds and hub rings is that which is set up by the transmission of the torque and this is easily determined for any specific design. Sample armature and hub rings have been made and tested with several amounts of welding. In the final design, a structure has been selected wherein the welds are much stronger than the steel in the arms. With this type of rotating part design, a much more rugged rotor is obtained than is possible by the use of castings and the old type of mounting punchings on dovetails. In addition to improving the mechanical safety of the rotor, the new construction is much more open and, by giving better ventilation, insures more output from the machine.

The number of stock sizes required is surprisingly small, considering the possible variations in shaft diameter and core length covered by the complete line of machines. It has been possible to design 68 combinations with only eight bar sections for the spider arms and two plate thicknesses for the hub rings, end plates and commutator supporting rings.

With this type of design, the factory cost of the rotor is not materially different from that of the cast construction when cast iron parts are strong enough for severe service. However, the structure is greatly superior to any cast design from the strength standpoint. Manufacturing time is also reduced by the elimination of the former machining of dovetail slots in the spider casting. This element is a striking example of important improvements which are frequently developed as the result of introduction of a new type of construction.

# Operation of Direct-Current Motors in Parallel and Series with Different Types of Load

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Much has been written concerning the operation of direct-current generators in parallel, but relatively little has been published on the subject of the parallel or series operation of direct-current motors. Perhaps the necessity for an article of this nature has never been felt, since the majority of the users of direct-current motors are well aware of what constitutes the proper type of motor and scheme of connection for a given application. The fundamental considerations governing this choice may not be so well known, however, and in this article, the reasons why motors are connected in series or parallel for different characters of load are developed; and the influence of the type of field winding and method of excitation used is given.

THE most familiar application of direct-current motors is that of single-armature machines operating in parallel from a constant-voltage bus. The motor may be shunt, compound or series wound, depending upon the speed-torque characteristic required. Series or compound motors are used, of course, where it is desired to secure high values of torque at low speeds or an increase in speed with a decrease in load. Shunt motors are essentially constant-speed machines.

### MECHANICALLY INDEPENDENT MOTORS IN PARALLEL

Typical speed-load characteristics of similar motors equipped with different types of field windings, when supplied with a constant voltage are shown in Fig. 1. Curve 1 shows that a motor which has only a shunt winding has a rising speed characteristic. For this reason, the shunt motor is usually equipped with a few turns of series winding, resulting in a characteristic as indicated in curve 2. Curves 3 and 4 indicate the characteristics resulting from the use of compound and series-field windings respectively. These curves are, of course, only examples and, by varying the proportions of total magnetization supplied by the shunt and series fields, it is possible to secure a curve lying anywhere between 1 and 4.

The speed-load characteristics of two of the most common types of load are shown in curves 5 and 6. Where friction constitutes the greater part of the load, as in elevators and cranes, as well as in the majority of steel mill, paper mill and machine tool applications, the speed-load characteristic will resemble curve 5. For

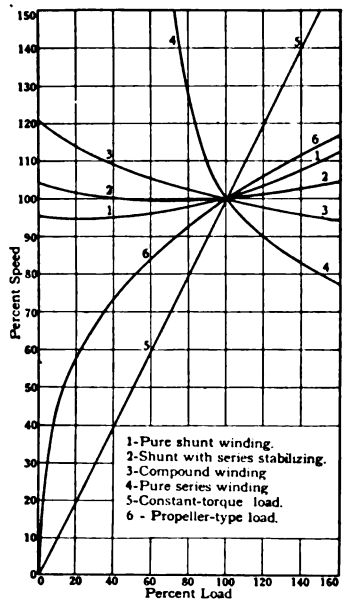


FIG. 1—SPEED-LOAD CHARACTERISTICS OF VARIOUS TYPES OF MOTORS AND LOADS

centrifugal pumps, fans, ship propellers, etc., the load varies approximately as the cube of the speed, resulting in a speed-load characteristic similar to curve 6.

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Where a motor is used to drive a generator which supplies power to a constant resistance, the load increases as the square of the speed giving a characteristic lying between curves 5 and 6. One application of this nature would be a motor-driven exciter supplying a constant-resistance field. For this discussion, however, it will be satisfactory to consider the two extreme conditions as covered by curves 5 and 6.

There is a definite intersection between curves 1 and 5, indicating that a shunt motor with only a shunt winding, even though it has a considerably rising speed characteristic, should operate in a stable manner on a friction load. However, where there is considerable inertia present, the load may increase rapidly with speed, being retarded only by the fact that the inductance in the armature winding limits the rate at which the current can increase. This explains why motors with rising speed characteristics often race, even on friction loads, where considerable inertia is present. The angle of intersection between curves 1 and 6 is quite small and in some cases disappears entirely, indicating that a shunt motor without any series turns may have a decided tendency toward instability when

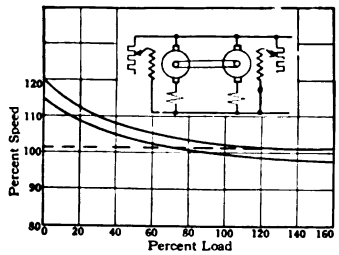


FIG. 2—SPEED-LOAD CHARACTERISTICS OF TWO MECHANICALLY-CONNECTED MOTORS WITH PARALLELED ARMATURES

driving a propeller-type load, even neglecting the effect of inertia. In view of the above, motors with rising speed characteristics are seldom placed in service, no matter what type of load they drive.

An exception to the above occurs in the application of direct-current equipment to ship propulsion where separately-excited shunt generators and motors are used. In this case the generator characteristic is sufficiently drooping to overcome the rising speed characteristic of the motor. This would not be a feasible arrangement, however, were the motor excitation not held constant with change in applied voltage.

Shunt motors without series turns, but equipped with compensating windings in the pole faces, often give speed-load characteristics which are essentially flat from no load to full load, the dip at fractional loads being practically eliminated. This is due to the fact that this winding decreases the armature distortion and increases the armature circuit resistance, both of which tend to flatten out the speed-load characteristic.

### MECHANICALLY CONNECTED MOTORS IN PARALLEL AND SERIES

Double-armature motors are used where the rating exceeds the capacity of one armature or where it is desired to reduce the motor diameter. Double-armature motors and motors mechanically tied together are, in the majority of cases, connected in series rather than in parallel. The reasons for this may be understood by reference to Fig. 2, which shows the speed-load characteristics of two armatures identical except for slight differences in shunt-field strengths. If these two armatures are placed on a common shaft or belted or geared to the same load and are connected electrically in parallel, they will, of course, run at the same relative speed as indicated by the dotted line, and one armature will carry almost twice as much load as the other. Any slight discrepancy in the characteristics of the two armatures due to different adjustments, unavoidable variations in construction, or even differences in temperature, will make it difficult if not impossible to compel each armature to carry its share of the load. This phenomenon is independent of the type of load and will become much more pronounced as the speed curves of the two armatures become more nearly flat, finally reaching a condition where one armature will carry the entire load and perhaps even drive the other as a generator. Obviously, for steep speed characteristics such as with heavily compounded motors, it becomes more practicable to operate the two armatures electrically in parallel.

When the armatures are connected in series, the load must divide in direct proportion to the voltages absorbed by the respective armatures, since the total load current flows through each machine. The voltage drop across each armature is, in turn, proportional to the respective field strengths, and the speed is determined by the sum of these field strengths. In case it is desired to operate two motors of dissimilar sizes mechanically connected together, they must, of course, have the same current capacity, their ratings being proportional to the respective voltage capacities. Then it is only a matter of adjusting the excitations of the two machines so that the desired speed is obtained and each motor absorbs its share of line voltage. Obviously, these considerations are not influenced particularly by the type of load being driven.

Although both armatures of double-armature motors are usually excited from line voltage, thus making their values of excitation independent of the division of voltage between the two armatures, this is not essential to proper operation. Mechanically-connected motors, the fields of which are excited from the voltages across their respective armatures, may be expected to perform in a perfectly stable manner, it being necessary only that both motors operate with some degree of magnetic saturation in order to provide a definite intersection between the magnetization curve and field resistance line. Of course, it is essential that neither motor possess a rising speed characteristic when operating as a single-armature unit.

By equipping each armature of a double-armature motor with a cumulative series and a differential series field, the latter carrying the current of the other armature, it is possible to cause the two armatures to oper-

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ate satisfactorily in parallel and still give a resultant speed-load characteristic which is essentially flat. This entails additional complication in both motor and control equipment, however, and should be avoided wherever possible.

MOTORS, MECHANICALLY INDEPENDENT, ELECTRICALLY IN SERIES, DRIVING CONSTANT-TORQUE LOADS

There are relatively few instances where motors, not tied together mechanically, are operated in series.

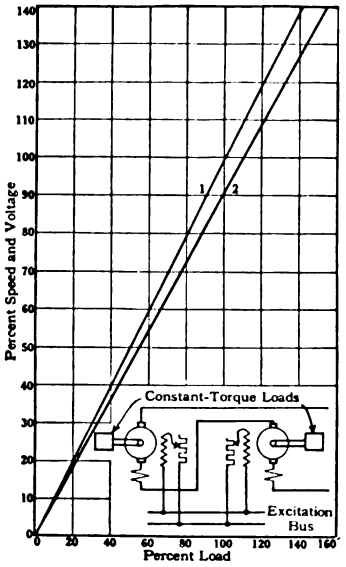


FIG. 3—CHARACTERISTICS OF TWO CONSTANT-TORQUE LOADS

As an example, take the case of two motors operating in series and driving separate constant-torque loads, curve 5, Fig. 1. Suppose, that both motors are excited at a constant value. In Fig. 3, which indicates the characteristics of this type of load, it has been assumed that, for the same speed, the load driven by motor 2 is 10 percent greater than that driven by motor 1. If the motors driving these two loads are identical and are supplied with the same value of field excitation, these curves may be taken to indicate the relation between the load supplied by either motor and the voltage absorbed by it. Since the load current must be the same for both motors, however, the ratio of load to volts must be the same, and this is impossible unless the speed-load curves of the two motors coincide. It is a characteristic of the series system that the motors tend to divide the voltage in such a manner as to draw the minimum value of load current. Therefore, the motor driving the load with the lesser torque requirements will instantly increase its speed to almost double value, absorbing practically the entire voltage, while the other motor will come to rest.

By strengthening the field of motor 2 or weakening that of motor 1, the relation between volts and speed for the two motors may be made to differ in such a way as to cause the two load-voltage curves to coincide. This means that the requirement that both motors carry the same load current will be satisfied for any value of voltage on either motor, as long as the sum of the two voltages is equal to line voltage. Obviously, this gives a very unstable arrangement as the slightest initial unbalance will result in one motor racing and the other slowing down or perhaps stopping altogether.

Motors equipped with series field windings, whether used in conjunction with constantly-excited field windings or not, may be expected to perform in the same fashion as those cited in the above example. This is because the field excitation in one machine always equals that of the other, regardless of voltage or speed, due to the series connection.

If each motor is equipped with a shunt field which is excited from the voltage drop across the motor, the tendency to instability is, if possible, even more pronounced than when both motors are supplied with constant excitation. Any momentary drop in voltage across either motor is accompanied by a corresponding decrease in field current, and therefore in torque. Since the motor does not then possess sufficient torque to meet the load requirements, it will slow down, resulting in a further decrease in voltage and torque. Since the effect is cumulative, the motor will come to rest almost at once. In the meanwhile, the other motor will absorb practically the entire voltage, but will run at considerably less than double speed due to its excitation being practically doubled as well.

MOTORS, MECHANICALLY INDEPENDENT, ELECTRICALLY IN SERIES, DRIVING NON-CONSTANT-TORQUE LOADS

The speed-load characteristics case of two motors operating in series and driving separate loads, each of which increases as the cube of the speed are represented by curves 1 and 2, of Fig. 4. It is assumed that both motors are excited at constant value and that, for the same speed, motor 2 carries 25 percent more load than motor 1. If the fields are so adjusted that the

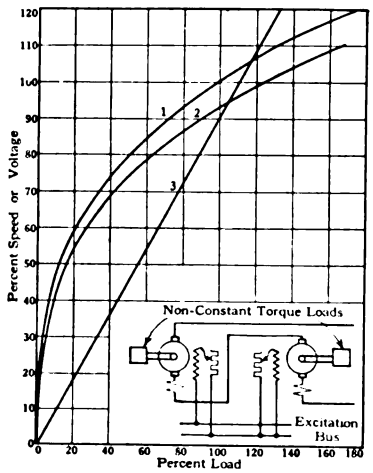


FIG. 4—CHARACTERISTICS OF TWO PROPELLING MOTORS OPERATING IN SERIES

ratio of volts to speed is the same for each motor, these curves may be taken to indicate the relation between the load supplied by either motor and the volts absorbed by it. The operating points of both motors will be on a straight line, such as curve 3, since any point on such a line has some constant ratio of load to volts which

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is a measure of load current. Curve 3 is drawn from the origin so that the sum of the voltages at the intersections of the two voltage-load curves is equal to line voltage. Obviously enough, this is a very stable arrangement since curve 3 has a definite intersection point with both 1 and 2. It is, of course, necessary that the sum of the individual voltages be equal to the total impressed voltage. In drawing in curve 3, it was assumed that 200 percent voltage was impressed across the two motors in series. It is also essential that neither motor possess a rising speed characteristic when operating as a single-armature unit.

From Fig. 4, it is apparent that the motor driving load No. 1 (which if both were at the same speed would carry less load and hence have less torque requirements) will run the faster and, of course, absorb the larger share of the voltage. Strangely enough, it will also carry more load than the motor driving the load

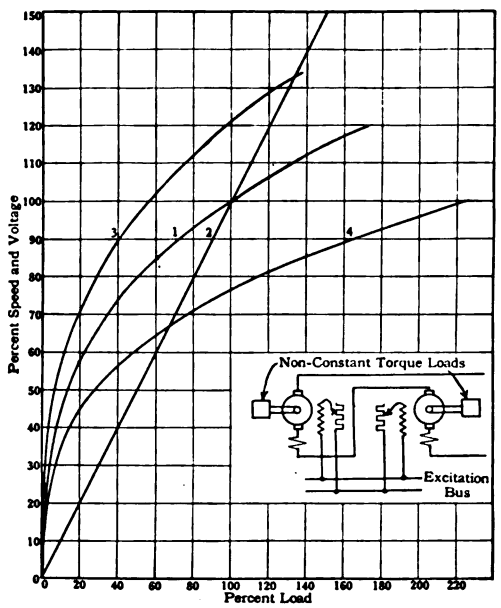


FIG. 5—CURVES ILLUSTRATING THE METHOD OF VARYING THE SPEEDS OF PROPELLING MOTORS OPERATING IN SERIES

with the greater torque requirements. It is, of course, possible to adjust the fields of these motors in such a manner as to cause the voltage-load curves to coincide. The two motors will then carry identical values of load although, perhaps, not at the same speed.

By further manipulation of the fields, it is possible to secure any desired division of load between these two motors. If the two loads possessed identical torque characteristics, curve 2 of Fig. 4 might be taken to indicate the voltage-load relation of the motor having the lesser ratio of volts to speed, and curve 1, that of the motor having the greater ratio of volts to speed. Contrary to what might be expected, and what obtains in parallel operation, the motor having the greater ratio of volts to speed, which is equivalent to a greater field strength, will run at a greater speed and carry considerably more load than the other motor. This is quite easily understood when it is considered that, with constant load current, the motor having the heavier field will naturally develop the greater torque.

From this discussion, it is readily seen that by proper manipulation of the constantly excited fields, it is possible to secure any desired load division between any two or more motors operating in series, provided the torque of all loads involved increases with the speed. Moreover, from the magnetization curves of the various motors, as well as the speed-torque relations of the driven loads, it is possible to foretell the speed, load, and voltage at which each of the motors will operate with a given set of field conditions.

Since electric drive for ships forms one of the most common applications utilizing direct-current motors electrically in series, most of the examples will be drawn from this field. With two or more propelling motors operating in series, there may be occasions when, for purposes of maneuvering, it is desired to operate the motors at different speeds. Let curve 1 of Fig. 5 represent the voltage-load relation of two identical propelling motors operating in series. Under normal conditions, each motor absorbs 100 percent voltage or one-half of line voltage and carries 100 percent current. Suppose it is desired to increase the speed of motor 1 by 10 percent, decreasing the speed of motor 2 at the same time in order to maintain the total load constant. If the total load is to be kept constant and the total impressed voltage remains unchanged, the operating point of either motor is determined by the intersection of that motor characteristic with line 2. Also the sum of the voltages at these intersections must be equal to 200 percent. An increase in speed of 10 percent is equivalent to an increase in load of approximately 33 percent. Therefore curve 3, corresponding to motor 1, must intersect line 2 at 133 percent voltage. Similarly curve 4, corresponding to motor 2, must intersect line 2 at 67 percent voltage. When the remainder of curve 3 is drawn in, according to the cube law, it is noted that at 100 percent voltage, motor 1 will now deliver only 56 percent load, indicating that the field must be strengthened to give a speed equivalent to the cube root of 56 percent or 82.5 percent of normal. Similarly, the field of motor 2 must be weakened to give a speed equivalent to the cube root of 225 percent or 131 percent at normal voltage.

Although Fig. 5 was used to make this example clear, this problem may be solved directly without the assistance of a diagram. It is necessary only to strengthen the field of motor 1 sufficiently to make it absorb 133 percent voltage at 110 percent speed. Similarly the field of motor 2 must be weakened sufficiently to cause it to rotate at 87.5 percent speed (cube root of 67 percent) with 67 percent applied voltage.

Another example is afforded by double-ended, electrically-driven ferry boats employing a propelling motor at either end of the boat. The boat moves alternately in either direction, power for propelling being furnished always by the aft motor. In the meanwhile the bow motor rotates at slip speed, which is about 80 percent of the aft motor speed, and supplies only

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enough power to overcome the resistance to movement through the water of its propeller, which is approximately 10 percent of the aft motor horse-power. Obviously, it is necessary to provide some means of reducing the speed of either motor when located at the bow. When this is achieved by placing the motors in parallel, each motor must be designed with a margin to permit of field strengthening when occupying the bow position. If, on the other hand, the two motors are placed in series, it is not necessary that any such margin be provided. The motor driving the boat will operate at full-field capacity, and the motor driving the bow propeller will have its field weakened to run at approximately 80 percent of this speed with 10 percent of impressed voltage.

Series motors, operating in series and driving propeller type loads, may be expected to operate in a perfectly stable manner. This is because any change in armature current affects the speed-voltage relation of each motor by an approximately equal percentage and does not, therefore, disturb the equilibrium of operation. For the same reason, compound motors (with shunt fields separately excited) constitute an entirely stable arrangement under conditions of series operation.

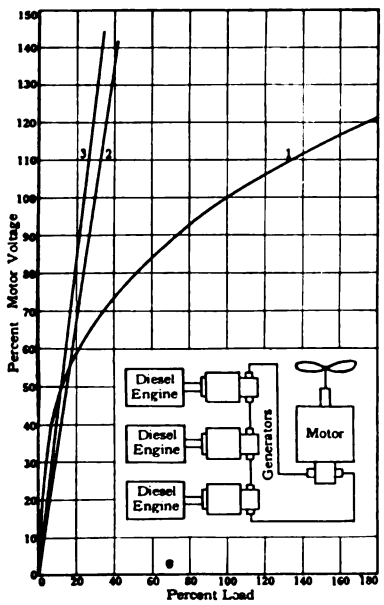


FIG. 6—THE EFFECT OF ENGINE FAILURE IN A SHIP PROPULSION CIRCUIT

Motors equipped with shunt fields which are excited from the voltage drop across their respective armatures will, in general, operate in an unstable fashion when placed in series, even if driving loads where the torque increases with the speed. As mentioned before, this is due to the fact that the torque decreases with a decrease in voltage, causing the motor to come rapidly to rest if once given a slight initial impetus in that direction. The tendency to instability is not so marked with this type of load, however, due to the fact that the torque requirements also decrease with a decrease in speed. In fact, it is quite conceivable that self-excited motors might operate satisfactorily in series on propeller type loads if equipped with heavy series windings and working at considerable magnetic saturation. The latter requirement is important since it is essential that a given percentage change in voltage and field current is not accompanied by as great a percentage change in flux which, with constant load current, is a measure of torque.

If two constantly-excited motors, one driving a constant-torque load and the other a propeller-type load, are placed in series, stable operation is achieved to, at least, a certain degree. The current in the circuit will be determined by the requirements of the constant-torque load and the division of voltage by those of the propeller load. This arrangement will be satisfactory with any number of motors in series as long as only one motor is driving a constant-torque load. The following example will serve to make this clear.

As mentioned before, a common application for ship drive consists of several separately-excited, direct-current generators in series, driven by Diesel engines, supplying power to the motor driving the propeller. In case one of the engines fail, for any reason, its generator will immediately have its polarity reversed and will tend to operate as a motor in the opposite direction. Obviously, this will have disastrous effects on the Diesel engine. The relation between load and voltage on the propeller motor, for a given field setting, is shown by curve 1 of Fig. 6. The torque required to overcome the friction of an ordinary Diesel engine is equivalent to approximately 30 percent of the normal full-load torque delivered at the shaft when operating under its own power. Therefore the voltage-load relation of the idle generator, now acting as a motor, may be represented by curve 2.

First, assume that three generators are used under normal operating conditions. The failure of one generator would result in a reduction in voltage to approximately 67 percent. Since curves 1 and 2 intersect at 55 percent voltage, it is clear that the idle generator will operate as a motor in the reversed direction at a speed corresponding to approximately 12 percent of the normal motor voltage. Due to the effect of armature resistance drop, which adds or subtracts depending upon whether the machine is operating as a motor or generator, this speed will be somewhat less than 36 percent of normal generator speed. With more than three generators in series, the same reasoning will apply, except that the speed of the dead engine and generator in the reverse direction will be greater.

Next assume that only two generators are used for normal operation and that one of these generators loses its voltage due to failure of its driving engine The voltage then drops to 50 percent of its normal value. Since 55 percent of normal voltage is absorbed by the propelling motor alone when operating at the current required to overcome the friction of the engine, it is clear that there will be no tendency for the idle generator to operate as a motor under these conditions. Instead, the propelling motor will operate at 50 percent of normal speed and voltage and 25 percent of normal current as indicated by line 3, in Fig. 6. It is customary, of course, to supply engine failure protection devices on all engine-driven generator sets for ship propulsion where more than two generators are in series.

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# The Development of Enclosures for Synchronous Converters

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Power Engineering Dept.,
Westinghouse Electric & Mfg. Co.

THE growth and congestion of our large, metropolitan districts has necessitated important changes in the design and installation of substation apparatus for street railway and lighting service. To meet the needs of this service, converting equipment must give the maximum possible output with the smallest overall dimensions, operate with minimum noise, and still provide unquestionable reliability and continuity of service. One of the principal difficulties in fulfilling all of these requirements is that of obtaining sufficient cooling air for the apparatus and the removal of the warm air from the substation. These requirements are being met most economically by the use of synchronous converters equipped with enclosures.

Obtaining suitable sites for substations to meet the growing demand for power in the congested areas of our large cities has become an acute problem. Land values in these districts have become so high that the first costs are almost prohibitive from an investment standpoint. In many sections substations have disappeared from view above ground altogether and have been located in the sub-basements of office buildings. The installation, operation and maintenance of conversion equipment in these underground substations have presented new problems to both the manufacturers and the users of this type of equipment to meet the needs of these applications.

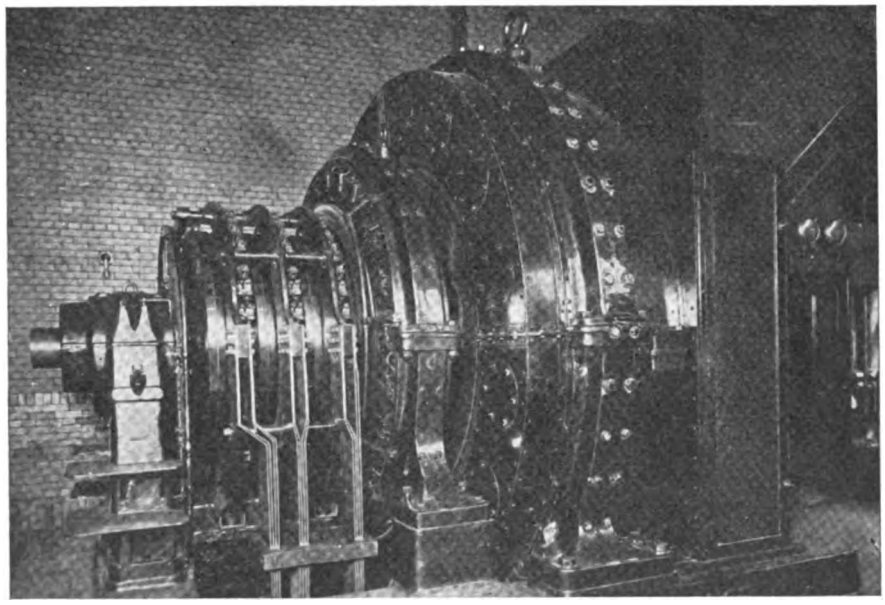

FIG. 2—SEMI-ENCLOSED, 13 000 AMPERE, 60 CYCLE BOOSTER CONVERTER*

In spite of the restriction of substation space, machines of still larger capacities are actually being required. Designs which facilitate the admission of large machine parts to such quarters, incidentally reducing interference to street traffic to a minimum, are necessary. Such installation of knocked-down parts requires more machine assembly work in the substation than would be necessary if shipment of completely assembled parts was possible. This erection work is usually handicapped by lack of overhead room and crane facilities.

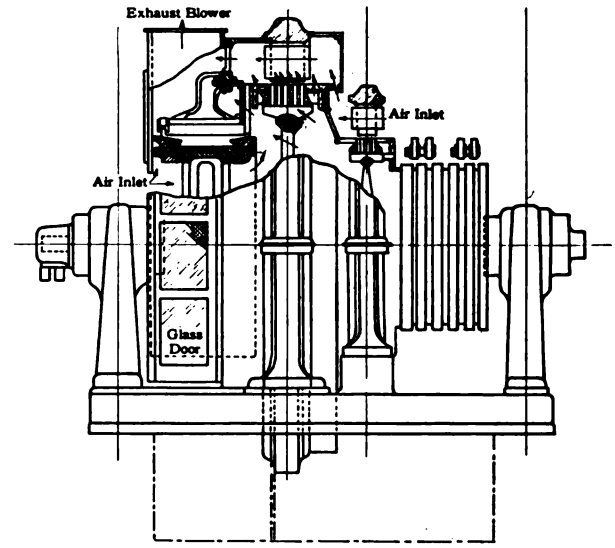


FIG. 1—SEMI-ENCLOSED, VENTILATION AND NOISE CONTROL SYSTEM FOR EDISON LIGHTING CONVERTERS

The successful operation of rotating electrical apparatus is dependent to a large extent upon adequate ventilation. After provision has been made for ducts for ingoing high-tension lines and outgoing low-tension cables, further space must be found for cooling-air ducts to these underground substations, as well as flues for the discharge of warm air.

The first installations of converters in sub-basements required little consideration of ventilation because of the small size of the units involved. As loads on these substations increased, more units—and usually larger units—were installed. Difficulties arose when substation temperatures reached such values as to be actually detrimental to the comfort and health of operating attend-

*Photographs of the 60 cycle installations are furnished by the courtesy of the Commonwealth Edison Co. of Chicago.

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ants, as well as to the life and maintenance costs of the apparatus. This problem was encountered in practically all of our largest cities by the public utility companies furnishing direct current for lighting service.

### SEMI-ENCLOSED CONVERTERS

Among the first efforts to reduce substation temperature was the use of the so-called semi-enclosed

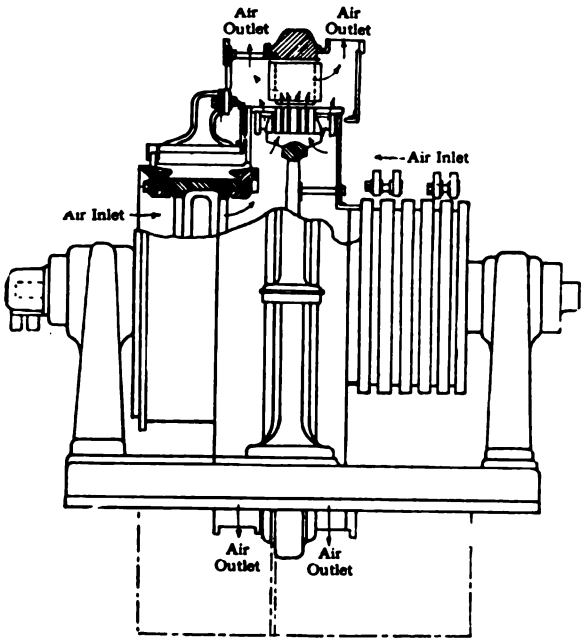


FIG. 3—SEMI-ENCLOSED, VENTILATION AND NOISE CONTROL SYSTEM FOR A RAILWAY CONVERTER

type of converter. The merits of this construction, as applied to both the Edison three-wire lighting and the railway converters were apparent to both the manufacturers and the public utility companies. One scheme of partial enclosures for lighting converters is shown in Fig. 1, and a photograph of a converter installed is shown in Fig. 2. This scheme of ventilation utilizes the natural air flow inherent in this type of apparatus. The room air is drawn into the machine from both ends and is discharged over the commutator into a flue which carries the warm air out of the substation. A small suction blower is required in the outlet flue to obtain best results with this scheme. The housing, end bell and baffle arrangement do not enclose the collector and booster elements, as these parts are not the source of any appreciable noise or heat. This arrangement also isolates the alternating-current brush rigging from the remainder of the machine so that copper dust thrown off from the alternating-current brushes will not be carried into the armature and field windings. Doors for entering the housing around the commutator are provided to permit maintenance of the direct-current brush rigging, and windows with hinged latches in the front of the housing are provided for observation of commutating performance.

With railway equipment, ventilation is secondary in importance to noise. The higher speed of 60 cycle railway converters tends to produce a windage roar from the rotating element, a whistling noise from air emanating from the commutator necks and a siren effect caused by the direct-current brushes passing over the undercutting of the mica between commutator bars. All of these possible noises can be considerably reduced by skillful design, such as the use of armature banding in the right place, commutator interneck supports, and proper proportions for the direct-current brush rigging. With the exception of installations in residential districts, no real occasion for enclosing railway converters would seem to exist.

The first effort to reduce noise in large, 60 cycle railway converters was the use of the semi-enclosed type of construction shown in Figs. 3 and 4. This type of enclosure is, in general, the same as that already described for the semi-enclosed arrangement used in lighting units. This arrangement on railway machines, being used chiefly to minimize noise, requires no separate blowers for taking away the discharge air. The intake air is drawn in from both ends of the machine and is discharged, by the blowing effect of the armature, out through the chimney vents on both sides of the machine at the top and bottom.

### TOTALLY ENCLOSED UNITS

Semi-enclosed converter housings having proved

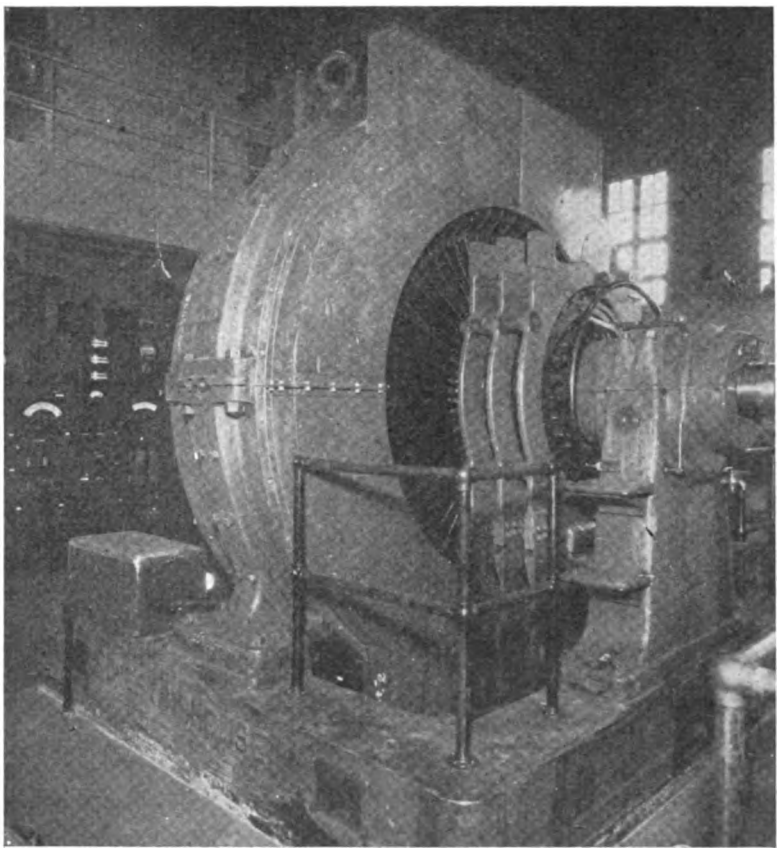

FIG. 4—SEMI-ENCLOSED, 3000 KW, 60 CYCLE RAILWAY CONVERTER

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successful, the idea of enclosure was soon extended and the totally-enclosed design developed, as illustrated in Figs. 5 and 6. With the totally-enclosed arrangement, the self-ventilating features of the armature fan action cannot be utilized, and some form of forced ventilation must be adopted. Various methods of forced ventilation have been tried. The scheme that has proved most satisfactory is to admit the cooling air under pressure from blowers through the commutator spider and around the commutator itself; and to expel the warm air over the collector to flues leading outside the building. Such a scheme obviously requires proper arrangement of baffles in the spiders of the machine and a housing with tight joints to prevent air leakage, so that the direction of air flow may be controlled.

With this enclosure arrangement, the ventilating air must pass through the converter in opposition to its natural direction. Considerable development work was necessary on actual installations before the system could be made to perform successfully. The chief problem was to prevent re-circulation and short-circuiting of the air inside the enclosure. The fan action of the commutator necks contributed chiefly to this re-circulation difficulty and considerable experimentation on baffle arrangements was necessary before the desired results were obtained. Air short-circuiting was occasioned by some of the ingoing air passing directly through the commutator and armature spiders and out the exhaust duct without passing through and cooling any of the heated parts of the machine. This was overcome by proper arrangement of the baffles on the rear of the armature spider.

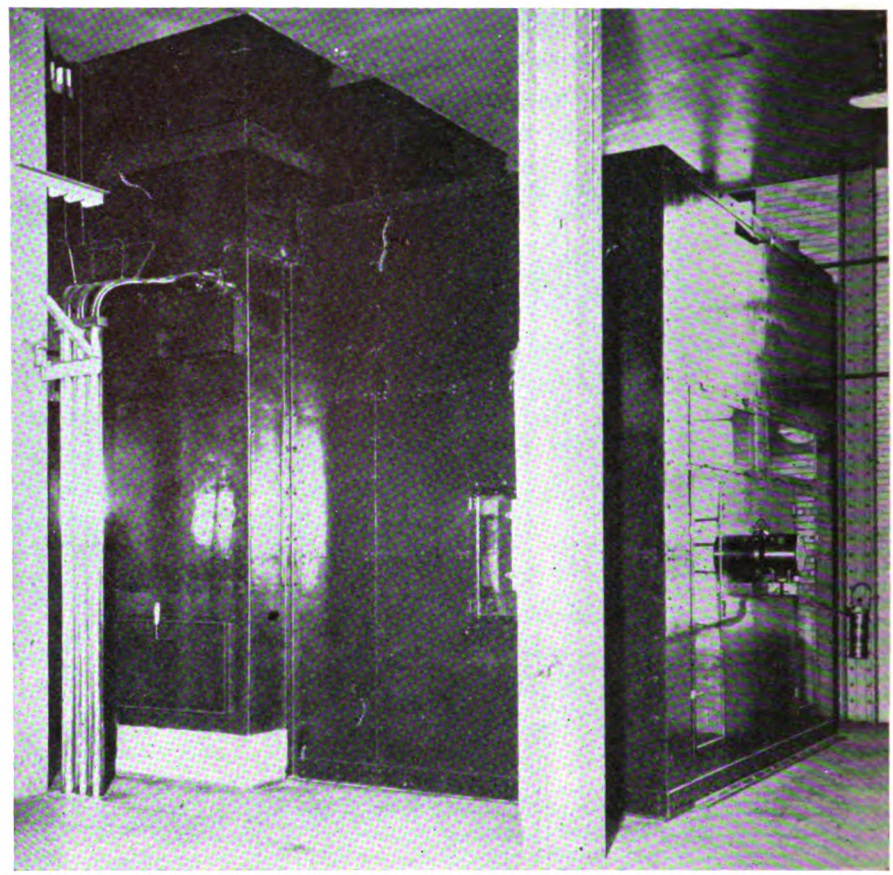

FIG. 6—TOTALLY-ENCLOSED, 13 000 AMPERE, 60 CYCLE BOOSTER EDISON CONVERTER

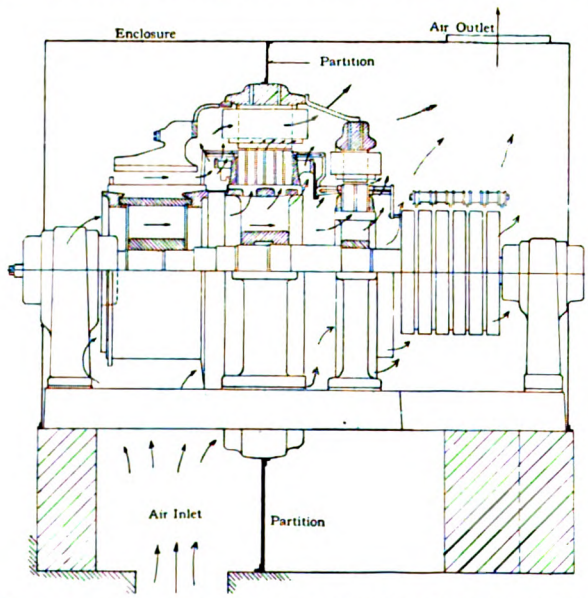


FIG. 5—TOTALLY-ENCLOSED, VENTILATION AND NOISE CONTROL SYSTEM FOR A 60 CYCLE LIGHTING CONVERTER

One of the obvious advantages of this scheme is in the admission of the ingoing cooling air directly to the commutator and direct-current brush rigging, where heat emanation is usually a maximum. This arrangement of air flow also insures against copper dust from the alternating-current brushes and collector rings being carried into the windings of the machine. This scheme does place parts nearest to the air discharge at some disadvantage, as the cooling air heats as it passes through the machine. At the present time, the temperature of the ingoing air, used as the cooling medium, is used in determining temperature rises for all parts of the machine. As the enclosed type of substation apparatus is becoming more generally used each year, some change in the basis of reckoning temperature rises from that previously applied to open type apparatus should be considered. Tests obtained on 13 000 ampere, 60 cycle totally-enclosed lighting converters show that satisfactory temperature rises on all parts of the machine were obtained at full load by the use of from 100 to 125 cubic feet of air per minute per kilowatt loss in the converter.

One of the outstanding advantages of the totally-

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enclosed machine has been the space economy effected. Considerable space has been saved by mounting the converter transformer close to the alternating-current

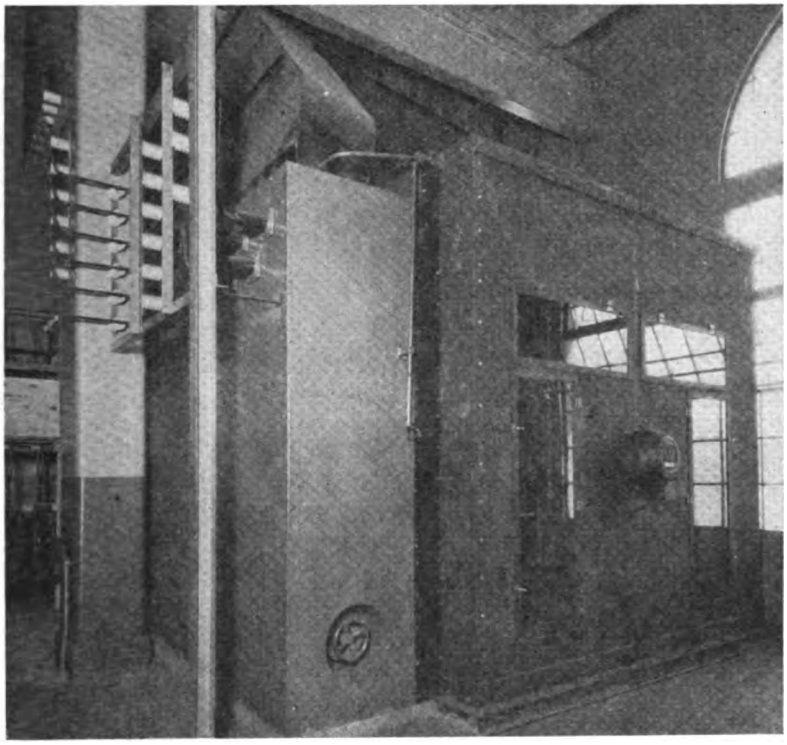

FIG. 7—TOTALLY-ENCLOSED, 3000 KW, 60 CYCLE RAILWAY CONVERTER

end of the converter as shown in Figs. 6 and 7. This arrangement not only saves considerable floor space, but simplifies the housing and the air ducts of the combined unit. The use of the transformer case as part of the converter enclosure requires insulating joints in the housing where it joins the transformer case. This is done to prevent injury to the operator from contact with the converter housing, in case a ground occurs on the transformer. The converter housing may also be insulated from the stationary part of the converter, if desired. A common blower for the transformer and converter, dividing its air supply proportionally to meet their individual requirements, is also made possible by this arrangement.

The total enclosure of railway converting equipment is necessary only when both noise elimination and ventilation are of importance. The enclosures of 60 cycle, railway converters with their higher voltages involve new problems, such as the danger of flash-overs, and higher voltages to ground. The greater clearance required between the machine and the housing, due to higher voltages, is apt to reduce the efficacy of the housing in reducing noise from the machine. A successful application of this type of enclosed equipment is shown in Fig. 7. The scheme of ventilation employed is, in general, the same as shown for the lighting-type machine in Fig. 6, with the booster element omitted.

The most difficult application of the enclosed type of converting equipment is met in certain substations where the air supply is limited by space considerations. Difficulty has been encountered in obtaining an adequate supply of intake air, and in disposing of the discharge air in some sub-basement substations. For this type of substation, a re-circulatory system of ventilation, air cleaning, and air cooling has been developed. The warm, discharge air is first passed through cleaners to remove the dust impurities carried away from the machines. It is next passed through water coolers and is then again ready for cooling purposes. The expense of this additional purifying and cooling equipment, together with the space required, are disadvantages that are at once obvious. The necessity for such installations, so far, has been quite limited.

### ENCLOSURES FOR 25 CYCLE MACHINES

This discussion of the totally-enclosed converter equipment has so far applied chiefly to 60 cycle applications of booster lighting and railway converters. Equally succesful applications have been made on 25 cycle lighting converters and the same principles apply to both the booster type and the field control type, examples of which are shown in Figs. 8 and 9. The scheme of enclosure used on the 25 cycle machine applies the same general principles as already given for the 60 cycle equipment. One of the differences on machines so far built is the by-pass provided under the machine on the 25 cycle apparatus for admitting some of the ingoing air direct to the booster element

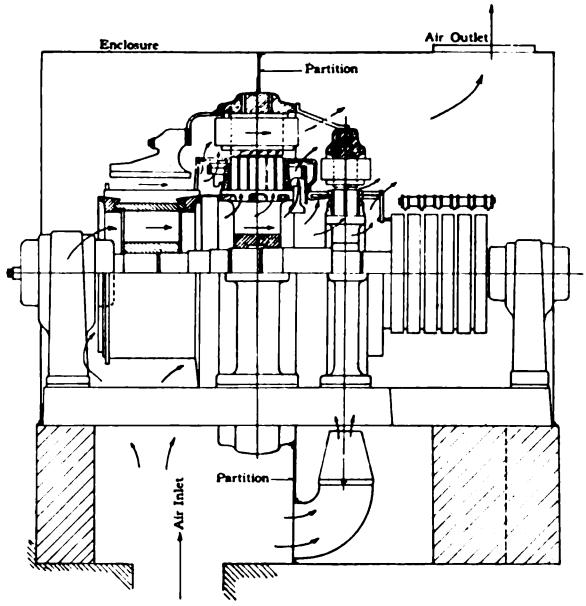


FIG. 8—TOTALLY-ENCLOSED, VENTILATION AND NOISE CONTROL SYSTEM FOR A 25 CYCLE EDISON LIGHTING CONVERTER

and alternating-current brush rigging. This feature can also be adapted to 60 cycle apparatus. Tests made on 4200 kw, 25 cycle lighting booster converters show that satisfactory temperature rises on all parts of the machine were obtained at full load by the use of from 125

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to 150 cubic feet of air per kilowatt loss in the converter.

The consolidation of synchronous converter and transformer units has been employed for 25 cycle apparatus to a somewhat greater extent than for 60 cycle equipment. In some installations, still greater saving in floor space has been accomplished by dividing the single, large, three-phase transformer as used on the 60 cycle equipment into two smaller transformers mounted symmetrically on each side of the collector end of the converter, and as close to the converter as possible and still allow clearances for necessary converter maintenance. Housing enclosures are readily adapted to such a scheme and effect the maximum saving in total floor space.

The economic advantage of using 60 cycle power for future extensions of Edison systems has caused some companies to install 60 cycle converters to operate in parallel with 25 cycle converters, and is causing other companies seriously to consider such an arrangement. Any instantaneous voltage reduction on either alternating-current supply system forces large currents through the converters, through the common direct-current connections. As the 60 cycle machines are the last to be introduced, and for a time are in the minority, it was at first feared that they might be seriously injured under these conditions. This situation was met by the development of the high-reluctance commutating pole, 60 cycle lighting converter and the reversing torque-motor control scheme of commutating pole-field excitation. The high-reluctance pole design feature was made possible by using a small number of commutator bars per pole. This feature increases the machines' momentary overload capacity materially and the reversing torque-motor control permits the same loads to be carried in inverted operation as in direct operation. Such a combination gives the best possible insurance against failure of 60 cycle lighting converters when used to supplement an existing 25 cycle system.

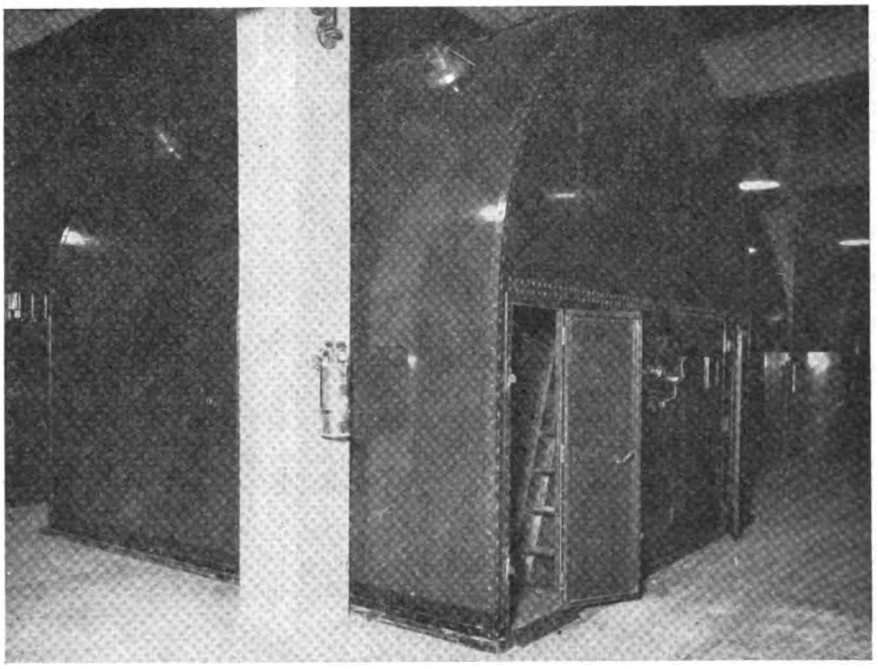

FIG. 9—TOTALLY-ENCLOSED, 4200 KW, 25 CYCLE BOOSTER EDISON CONVERTER*

*This photograph is furnished by courtesy of the New York Edison Co.

## SUMMARY

In the application of synchronous converters in metropolitan districts, it can be safely assumed that for surface substations, where noise is not a factor, standard open-type units will continue to be generally used. For extensions to existing substations where noise or ventilating factors require consideration, and where space limitations preclude the possibility of totally-enclosed apparatus, the semi-enclosed type of design will be required. For all new substations where noise or ventilation must be given special consideration, and wherever space can be obtained for the ventilating ducts and accessories, it is safe to predict that the totally-enclosed apparatus will be applied. In the early stages of this development, the first results indicated that enclosures required some sacrifice in machine rating. As the design of enclosures and machines has been improved, the more recent results obtained indicate that increased capacities are possible as a result of the use of forced ventilation when it is efficiently directed in its flow through the machine.

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# Apparatus Used in the Investigation of Lightning Phenomena

EDWARD BECK
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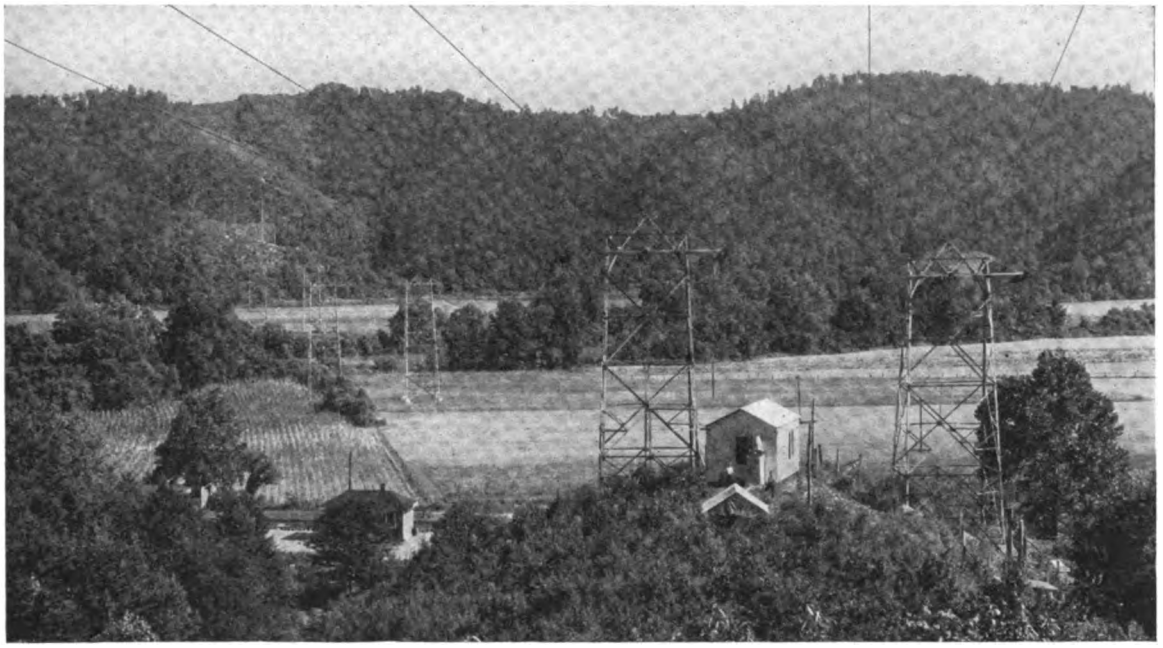
Westinghouse Electric & Mfg. Co.

LIGHTNING has long been a great trouble maker. Its assaults on the transmission of electrical energy, while not more virulent than heretofore, have, because of the expansion of power systems, assumed such importance in the past ten years that strenuous efforts are being made to solve its method of attack, to learn the behavior of the disturbances it causes on transmission lines and in apparatus, and to develop new and more effective ways of combating its interference with the operation of large electrical systems. To this end, newly developed measuring devices and a crew of trained observers have been posted in the foothills of the Smoky Mountains in Tennessee where, with the co-operation of the Aluminum Company of America, to whose transmission lines the instruments are coupled, data is being collected which bids fair to mark a new era in the study of lightning phenomena*.

The chief trained observer in this search for new truths is the so-called cathode-ray oscillograph**, an inanimate but ever-ready watchman which automatically records the performance of the lightning. To supplement the information secured by this remarkable instrument, the investigation employs additional apparatus in the form of klydonographs, osisos, and a photographic range finder consisting of special cameras which will photograph the entire horizon on a single plate.



ONE OF THE LIGHTNING OBSERVATION STATIONS LOCATED UNDER THE TRANSMISSION LINES OF THE ALUMINUM COMPANY OF AMERICA, IN THE SMOKY MOUNTAINS OF TENNESSEE

The laboratory between the two towers houses the cathode-ray oscillograph and associated equipment. It is built of wood but is screened from atmospheric electrical discharges by a wire mesh which entirely closes it. Concrete foundations are provided for the oscillograph and heavy rotating machinery. Because of the great heat experienced in these locations during the summer months, the houses are painted with aluminum paint. This paint decreases the temperature inside to about 10 deg. F. below what the temperature would be if paint of other colors had been used. The edge of the fenced yard containing the klydonograph and potentiometer can be seen on the down-slope side to the right of the transmission towers. Each of the observation stations is equipped with a water-purifying plant, electric cooking facilities, and an electric refrigerator.

The oscillograph is the keystone of the installation. It discloses characteristics of transients about which nothing has been determined in the past. The disturbances which are generated on the wires of transmission lines during thunder-storms consist of exceedingly high voltages, which may change at the rate of hundreds of thousands of volts in a millionth of a second. These voltages are generally of very short duration. The total disturbance may pass a given point in a few millionths of a second. The exact characteristics of these volt-

*The purpose of this investigation and the needs for it were described by A. L. Atherton in an article in the *Electrical World*, for July 28, 1928.

**Described in the JOURNAL for August 1927, p. 384.

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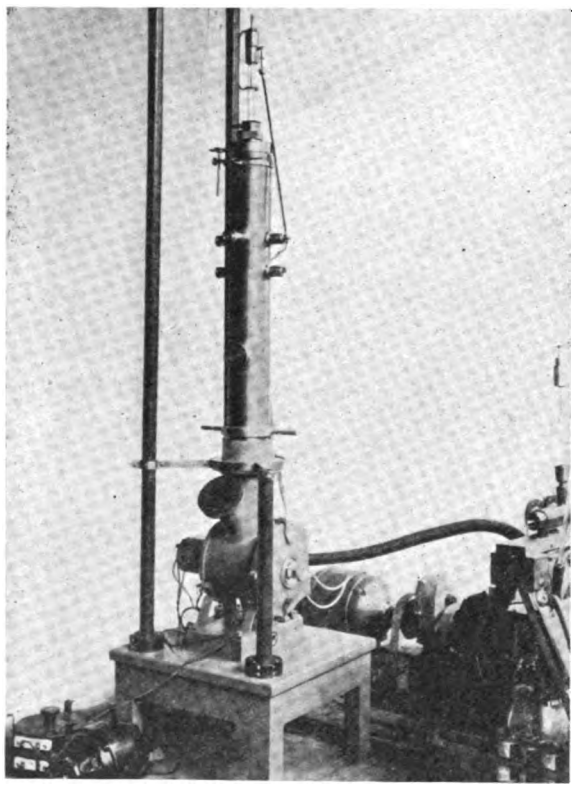
ages have baffled scientists for many years. To know all about them, it is necessary to record the disturbance, or transient in detail. Until a short time ago, this was considered impossible. Ordinary measuring instruments cannot be used for such studies because the inertia of the moving parts is too high to permit them to react to the rapidly occurring lightning disturbances with sufficient speed. The type of cathode-ray oscillograph developed by DuFour in France has for its moving parts a ray of electrons, whose inertia is practically nil. Therefore, if reacted upon by the proper means, it will follow accurately the most rapid conceivable changes. Intervals of a tenth of a millionth of a second can be distinguished easily. Great strides have been made in advancing the art of cathode-ray oscillography to the point where natural lightning disturbances, whose time of occurrence cannot be foretold, may be recorded. Dr. Harald Norinder, a Swedish scientist and consulting engineer for the Westinghouse Company, has improved the cathode-ray oscillograph to a type which is automatic and which is always on the watch for passing electrical transients. The Norinder oscillograph is the only device which will record, without the use of external switching devices, a complete transient from its beginning to its end. This is accomplished as follows:—When a storm is reported, the oscillograph is evacuated and the cathode beam is established. It is left in this condition for the duration



THE CATHODE-RAY OSCILLOGRAPH AND SOME OF ITS AUXILIARIES

The oscillograph itself, the central vertical instrument, is about seven feet long and weighs about 200 lbs. The cathode stream is formed in the glass tube at the top, the cathode being just above the glass and the anode immediately below. The photographic film is located in the drum-shaped compartment at the bottom of the oscillograph. Records can be taken with the film stationary or rotated at any speed up to 6000 r.p.m. by the motor in the circular housing on the left. The covered port just above the film compartment is used in adjusting the film or can be opened to watch the transient records on a florescent screen substituted for the photographic film. The oscillograph is evacuated by the pumps to a pressure considerably below the four thousandths of a millimeter of mercury operating vacuum. Air of the proper amount to maintain the working pressure is continually admitted by a tiny cup-shaped valve at the upper end of the long, slender, inclined tube near the electrodes. By this means the vacuum is exactly controlled and all gases formed in the oscillograph are blown out. This valve which must accurately control such minute quantities of air is in itself a marvelous device.

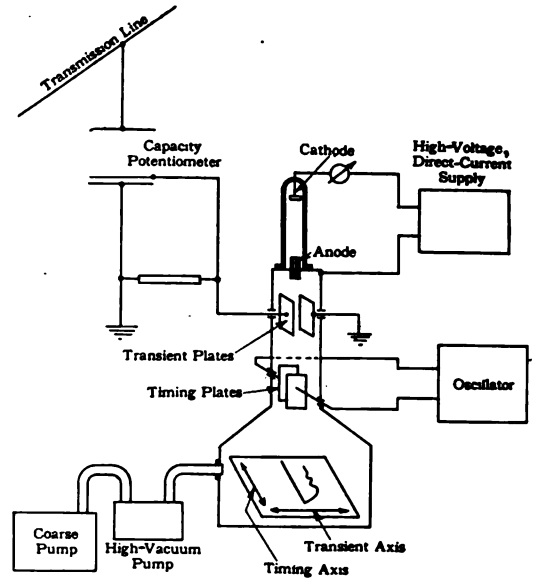
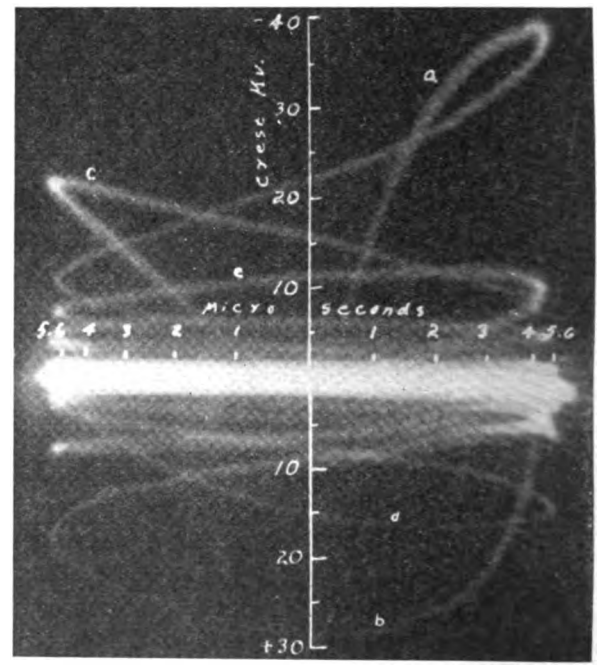



DIAGRAM OF CONNECTIONS OF THE NORINDER OSCILLOGRAPH




A RECORD OF A TRANSIENT ON A TRANSMISSION LINE MADE WITH THE CATHODE-RAY OSCILLOGRAPH

This record was made with the film stationary and an oscillator used to give the timing axis. One sweep across the film represents 11.2 millionths of a second. Periods of time as low as 0.1 millionths of a second are easily distinguished.

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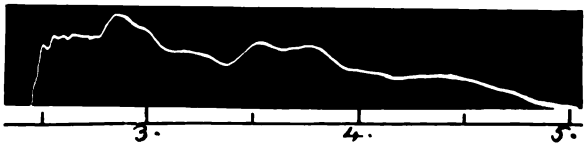
of the storm. If the cathode beam were permitted to strike the photographic film for this period, it would fog the film so badly that no record would be secured. In the Nordinder oscillograph the beam is kept off the film until a disturbance arrives, when it immediately, because it has no inertia, moves on to the film and makes a record.



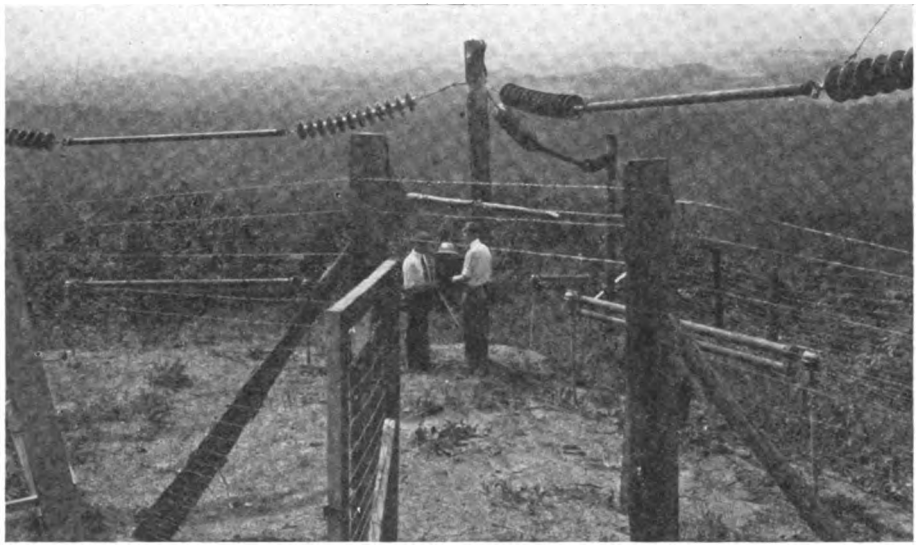

A CATHODE-RAY OSCILLOGRAM OF A TRANSIENT ON A TRANSMISSION LINE TAKEN WITH THE ROTATING FILM DRUM

Showing the remarkable detail obtained. The cathode-ray oscillograph makes a complete record commencing with the very beginning of the transient. This film was made in 1927 by Dr. Norinder, who secured the first oscillograms of lightning on transmission lines.

For this instrument to be in an operating condition, it is necessary to produce inside of it a pencil of electrons, or as it is more commonly known, a cathode ray. This is accomplished by applying a high, unidirectional voltage between the cathode located at the extreme top of the instrument and the anode located a short distance below the cathode. The anode contains a small hole, through which passes the electron beam generated at the cathode. At the bottom of the oscillograph is located a photographic film upon which this cathode beam impinges. Although the beam itself is invisible to the eye, it will leave a visible trail on a fluorescent screen or produce on a photographic film the same effect as a beam of light. Wherever the beam strikes there will appear a spot, or if the beam is moving, a line, after the film is developed. The electron beam may be bent back and forth by properly placed coils or plates whose fields of force are determined by the lightning disturbance. If a transient occurs, these electric fields vary with it. The electron beam follows the changes in the field, thus recording the history of the transient on the photographic film.

In order to produce a cathode beam in the oscillograph, it is necessary that the air pressure in it be reduced to the order of 4 to 8 microns, a micron being the pressure exerted by a column of mercury 1/1 000 000 of a meter in height. When we consider that the pressure of the air in which we live is equivalent to a column of mercury roughly ¾ of a meter high, we see that the pressure in the oscillograph is of the order of 1/180 000 of the surrounding air. To secure this low pressure and maintain it in the instrument requires a highly efficient system of vacuum pumps. The pumping system is one of the most important adjuncts of the oscillograph. Two stages of pumps are used, the first a so-called rough pump which will produce a fairly low pressure when exhausting into the open air. The second stage is a high-vacuum pump which exhausts into the low pressure created by the first. The action of this pump depends on the inertia of the gas molecules. The pump consists essentially of a spiral groove cut on a cylinder which revolves rapidly in a shell with a mechanical clearance of only a few thousandths of an inch. When the cylinder rotates at high speed, the inertia of the molecules caught in the spiral groove carries them out of the chamber to be evacuated by the rough pump. The rough pump is an ordinary oil-submerged vacuum pump.

With the oscillograph and the proper pumping system there is still needed a source of high, unidirec-



ONE OF THE POTENTIOMETER AND KLYDONOGRAPH YARDS

This yard is located on the other side of the Chilowee Mountain from the station shown on page 593. The operators here are changing a film in the klydonograph mounted on the center pole. The pipes form the condenser plates of the potentiometer, the three between the insulator strings being connected to the three-phase, 154 kv transmission line. The bottom ones of the three pairs are connected to ground, and the ones immediately above them are connected to the klydonograph. The fence serves the double purpose of keeping danger out and danger in, as it was found necessary to protect the equipment from prowling animals which inhabit the country and to prevent possible intruders from coming in contact with high voltage.

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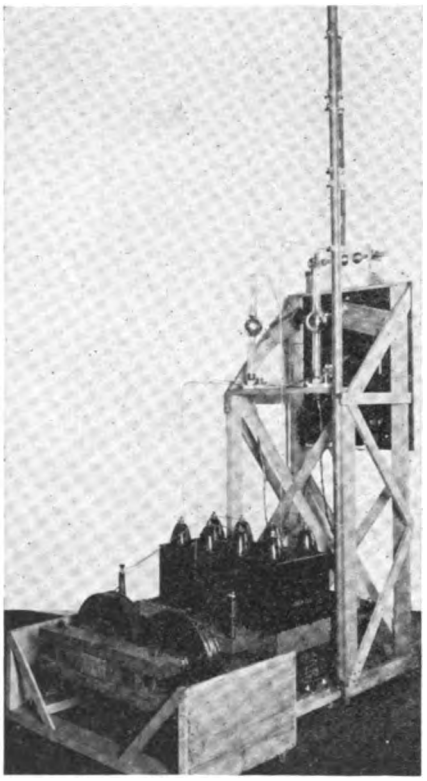
tional voltage to generate the cathode stream. This voltage must be of the order of 30 000 to 60 000 volts and must be uniform. It is obtained by means of transformers and high-voltage rectifier tubes. The transformers step up the voltage from 110 volt supply to the desired value, at which it is rectified by the vacuum tubes and filtered by a bank of high-voltage condensers. The current drawn from this source is of the order of only three-tenths of a milliampere. Although this is but one-tenth of the plate current of a radio receiving tube, it is sufficient to provide enough electrons for a sharp photographic reproduction of the transient.

To obtain a clear record of transients, it is necessary to have a time axis on the film. For relatively slow phenomena, this axis is secured by rotating the film on a cylindrical drum at an approximate speed of 7 200 r.p.m. The film travels at about 12 000 feet per minute. This may appear to be a high speed but it is suitable only for the measurement of relatively slow electrical transients. For rapidly occurring transients much higher speeds are necessary. These cannot be obtained by mechanical means. For this purpose, the

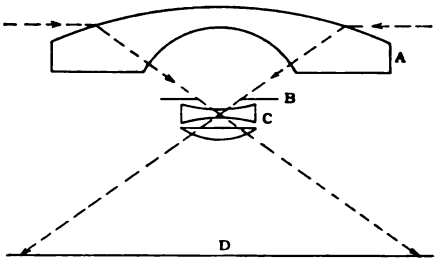


THE RECTIFIER EQUIPMENT

Two special high-voltage rectifier tubes are mounted behind the control panel with the four condenser cases mounted on insulators at the bottom of the frame. The high-voltage transformer is in the wood frame in the foreground.

film is left stationary and the electron beam is caused to travel back and forth across the film at a predetermined rate. The most convenient way of doing this is by means of an oscillator which impresses a frequency of high known value on a deflecting system at right angles to the system producing the voltage deflection. The oscillator being used for this purpose is very similar to the oscillators used in radio practice. Its frequency is readily adjustable between wide limits.

One of the more prominent of the other devices which will help to expose the mysterious ways of lightning is the klydonograph*. It records the maximum




ARRANGEMENT OF LENSES IN CAMERA TO PHOTOGRAPH THE ENTIRE SKY

*A* is the lens with spherical surfaces which refracts the rays of light into a cone of about 90 degrees. *C* is a wide angle lens system giving a projection on the film *D*. At *B* is a provision for a color filter, since it is difficult to make a whole sky system achromatic. With this projection the photograph of a circle will appear as an elipse toward the edge of the film; one diameter always remaining the same, the other lengthening. Equal distances measured on the film represent equal angles in the sky. Whole sky pictures taken with a camera are quite distorted near the edges. However, sections of a picture may be enlarged, and corrected by reversing the action of the lens. This converts any section into a normal view as taken by the usual camera.

transient voltage occurring on transmission lines and the time of their occurrence without giving details of their shape or duration. Until the advent of the cathode ray oscillograph it was the most important instrument for investigation of lightning disturbances on transmission lines. Much valuable data has been gathered by it during the past four or five years. In this Tennessee investigation, it supplements the data obtained by the oscillograph, and will measure the magnitude of surge voltages occurring at different points along the 154 000 volt transmission line.

The osiso is a small oscillograph used for the recording of voltages or currents. It is used, in these lightning tests, to locate the position of the lightning stroke. This is done by measuring the time interval between the lightning stroke and the arrival of the thunder noise at the observation station. For the recording of the thunder, it is coupled to a microphone which picks up the thunder noise, transforms it into electrical energy, as does the microphone in a radio broadcasting station, and makes a record of the noise current on the film of the osiso. The osiso is automatically put into operation by the electrical disturbance on the transmission line. The time elapsed between the lightning stroke and the thunder is shown by the interval on the osiso film between the instant it begins to run and the instant the noise record begins. Installation of two microphones at separated points permits the location of the lightning stroke by triangulation, the distances being calculated from the time elapsing between the lightning stroke and the thunder.

*Articles describing the klydonograph were printed in the JOURNAL for Jan. 1927.

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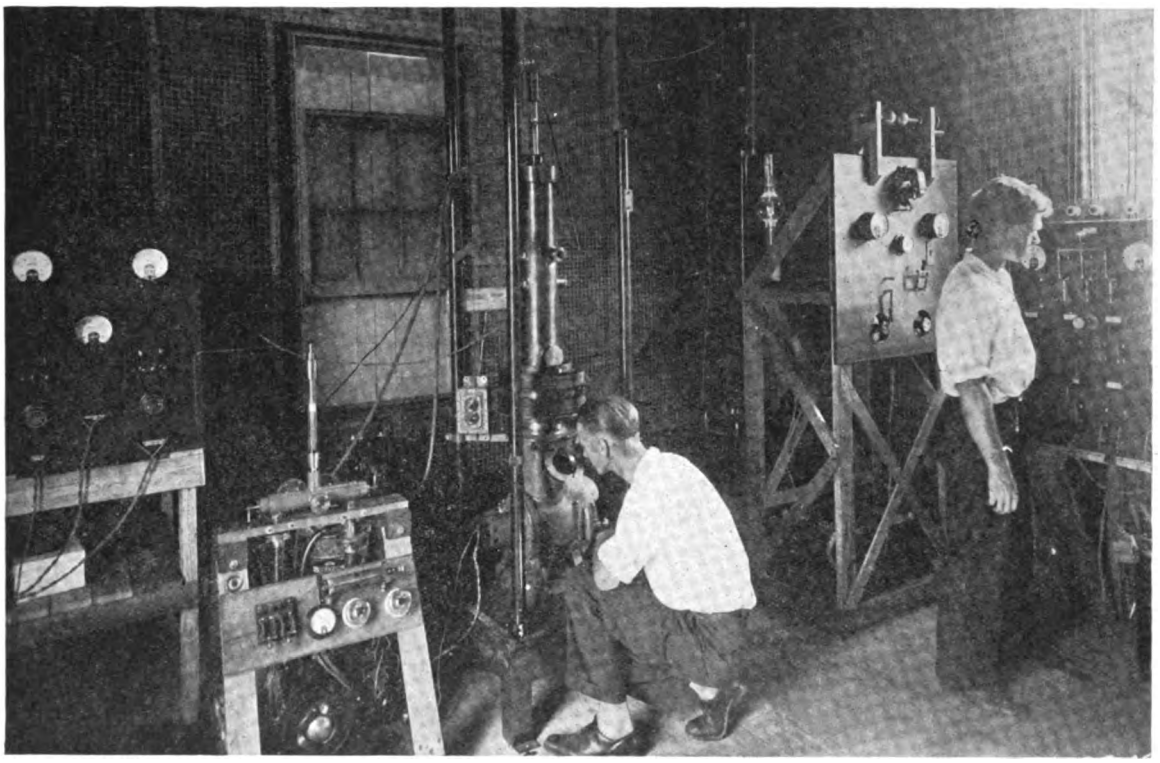
To procure further information about the lightning stroke and to check the location found by the osiso, the observation stations are fitted with a special form of camera which will photograph the entire horizon at once. Any lightning stroke occurring will record its appearance on the photographic plate. With two such cameras, the position of a stroke can be determined accurately. The visible characteristics of the lightning stroke will be recorded by this camera. In conjunction with the data obtained with the cathode ray oscillograph, it is expected that some relation will be found between various characteristic lightning strokes and the disturbances which they cause on high-voltage transmission lines.

Radio receiving sets and a special form of relay which rings a bell are employed to herald the approach of a storm. They give the signal for action. All necessary apparatus is put in operation and the oscillograph tested, so that it is ready when transients begin to arrive. The bell also announces the arrival of transients while the recording process is going on, so that the operators can tell that exposures have been made on the oscillograph film.

The last but not least piece of apparatus is the power source. In this remote Tennessee location there is no low-voltage supply available. The transmission line on which the tests are being made operates at 154 000 volts which is, of course, unsuitable for use in the laboratory. Rather than to supply transformers to step this potential down to 110 volts, it was found cheaper and more convenient to install gasoline-engine-driven generators to furnish 110 volts at 60 cycles and also direct-current for the operation of the oscillograph, its accessories, the lighting system, electric refrigerator, and cooking facilities.



THE TOOLS FOR LIGHTNING STUDY INSTALLED IN ONE OF THE OBSERVATION POSTS

The panel in front of the operator at the right controls the gasoline-engine driven generators. Behind him is the rectifier tube and panel which provides high-voltage direct current for the oscillograph. The coarse vacuum pump is behind the cathode-ray oscillograph in the center and the fine vacuum pump is beside the oscillograph on the left. The oscillator control panel is at the extreme left. The screen for electrostatic protection of the instruments can be seen covering the walls and ceiling of the building.

Engineers have been attempting for many years the vivisection of thunderstorms. With the armamentaria described here, the answer is not far off.

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# Field Balancing of Rotors

JAMES J. RYAN
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Westinghouse Electric & Mfg. Co.

WHEN a large rotating electrical machine is installed in the field, it is often necessary to adjust the mechanical balance before it can be placed in service, or to correct for a vibrational disturbance which may occur during the course of its operation. Of kindred importance is shop balancing in the factory, where the higher speeds and greater masses of present day rotors require an exactness of balance difficult to obtain. It is for the purpose of converting a theoretical solution of this specific balancing problem into the channels of practical use that the following paper is written; but the theoretical and practical treatments of the problem given will also serve to throw light upon the simple fundamentals which are so important in the study of the phenomena of vibration.

The specific problem refers to a method of field balancing large rotors of the conventional type, with the minimum number of balancing trials. Different abstract methods of balancing rotors other than the conventional type, i.e., rigidly coupled rotors having multiple bearings, and rotors which do not have a symmetrical mass distribution, have been developed, but they are rather inefficient and require much experience in their use, as the complexity of such a system eliminates the possibility of isolating the unbalance forces. Usually, balance is restored to such machines by a long series of balance weight adjustments, determined by trial and based upon balancing experience.

For single rotors, mounted upon two bearing pedestals, and having approximately symmetrical mass distribution, referred to as the conventional type, field balancing has, in general, been accomplished by the trial and error method, with the aid of shaft "marking", and vibrograph readings of amplitude. A mark is made on the shaft at the bearing pedestals during the rotor vibration to indicate the side of the rotor that is carried to the outside of the vibration orbit by the centrifugal forces of the unbalance. The position of the unbalance in the rotor body is considered to be approximately 90 degrees ahead of the mark of eccentricity, and the position at which to attach the correction weights on the rotor is then 90 degrees behind this mark. The effects of the various size balancing weights attached to the rotor are observed from the vibrograph readings of amplitude. Several trial runs are necessary before the trend of the vibrations to increase or recede with various correcting weights at the indicated rotor position is ascertained. The procedure is to individually balance each end of a rotor until the vibrations are of small magnitude, then to return to the first end to correct for any disturbance which may have been induced when the second end was balanced.

A scientific method of balancing this type of rotor, eliminating the necessity of a large number of balancing trials, is of great practical importance in the solution of field vibration problems. The method here described involves a straight-forward calculation of the original unbalance from five vibration trials in succession, and is free from the chance element of the trial and error method. The accuracy of the calculation, however, is dependent upon the type of vibration instrument used in obtaining the values of the maximum pedestal motions; a recording vibrograph is the best instrument for this purpose but, with some experience, an arrangement of dial gauges is sufficient. It is necessary to obtain relatively few physical quantities for this calculation,—the maximum amplitudes of the two bearing pedestals for the five vibration trials, and the size of the two identical temporary balance weights attached to the rotor is all the information that is required.

The calculation of the unbalance is a graphical conversion of the amplitudes of the rotor motions into unbalance forces, whereby the inherent unbalance forces in the rotor are isolated. The details of the calculation involve the simplest type of vector analysis, and after the fundamentals of the problem are grasped, the solution becomes more or less a mechanical process. The calculation is entirely graphical, and the solution is obtained in a short time. The solution determines the location and size of the correction weights to be attached to the rotor for final balance.

To determine the necessary data for the solution of this problem, a series of five trial runs are made with the rotor in five different conditions of unbalance. During each trial, vibrograph readings are taken to obtain the maximum amplitudes in the lateral direction of the two bearing pedestals. The initial run is made with the rotor in its unbalanced condition. For the second run, two temporary balance weights of equal magnitude are attached, one at each end of the rotor, in balance planes designated as 1 and 2, located equidistant from the center of gravity. These weights are placed in the same axial plane, i.e., the angle between them is zero. It is important that these weights have sufficient mass to disturb the balance of the rotor measurably, and they are selected from a consideration of the centrifugal forces of unbalance, the rotor mass, and shaft and pedestal flexibilities.

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In the remaining trials, the same balance weights are used. For the third run, the weight in one of the balance planes is shifted 180 degrees, the other weight remaining as in the second run. For the fourth run, the weights in both balance planes are 180 degrees, from their positions in the second run. For the fifth and last run, the weights in both balance planes are shifted 90 deg. in the same direction from their positions in the fourth run. Accurate measurements of the pedestal vibrations from the vibrograph records of each trial form the basis for the graphical calculations of the rotor unbalance.

The machine is operated at a constant speed of the same magnitude for all the balancing trials. This speed should not fall within a critical or resonant range of vibration, for in such a state, a slight variation in speed creates a large variation in amplitude. The operating speed of rotors is generally far enough below the critical to permit balancing, but where resonance is evident a lower speed is used.

The balance rings in each balancing plane are divided off and plainly marked, with the balance weight holes numbered consecutively. These holes in both balance rings are numbered identically when viewed from one end.

The vibrograph is attached in such a manner that the floor vibrations are eliminated from the readings of amplitude. This is accomplished by mounting the vibrograph upon a heavy mass supported on springs, or hung from an overhead crane. Dial gauges (0.001 in. reading) may be used in a similar manner, or may be attached rigidly to the pedestal with the stem resting against a seismic weight. It is important that the rotor be freely supported upon two bearings. It may be self driven, belted or flexibly coupled to another machine, or driven by a rigidly coupled machine with a comparatively small rotor, such as an exciter. It is necessary to observe these conditions to obtain the true motions of the mass, considering only two degrees of freedom. The methods mentioned are some of those ordinarily used in the field in connection with this problem.

The rotating element of the machine, consisting essentially of a rigid cylindrical mass, is supported upon flexible members, the shaft ends and the bearing pedestals, which transmit to the foundation the periodic forces set up by the unbalance during rotation. As the rotor body traverses an orbit in vibration around its static position, the pedestals at the centerline of the bearings are constrained to move with an elliptic motion corresponding to their relative flexibilities in the lateral and vertical directions. The maximum amplitudes occur in the lateral direction, the direction of least rigidity; hence, for convenience, all measurements are taken in the lateral (horizontal) plane. These lateral displacements are directly proportional to the disturbing forces, and from the analysis of the maximum pedestal movements, knowledge of the amount and position of the offending unbalance may be readily obtained. The process is the reverse of the course usually followed in the solution of vibration problems, where, with given unbalance force, it is required to determine the motions of a system.

A complete solution of the material points of the problem is given. An examination of the primary equations of vibration for this rotor system will determine the factors which correlate the unbalance forces and the amplitudes of motion. In explanation of the effects produced upon an unbalanced rotor by the balancing procedure outlined above, the forces in a rotor having a known unbalance will be analyzed for each trial condition. It will be observed that certain prominent characteristics of the force vector

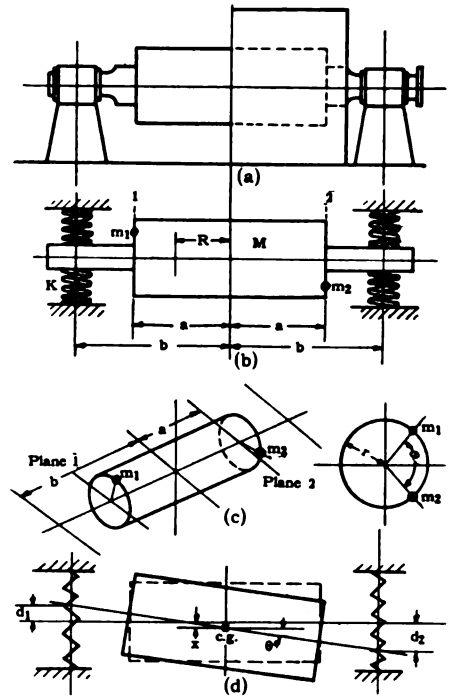


FIG. I

diagrams point the way directly to the solution of the problem where the original unbalance is unknown.

## FACTORS INVOLVED IN THE THEORETICAL ANALYSIS

The conventional type of electrical rotor, shown in Fig. 1 (a), is one approximately symmetrical with respect to centerline dimensions, with bearing pedestals at each end, and not rigidly connected to another machine. The temporarily added unbalance weights are placed in balance planes located at equal distances, axially and radially, from the center of the rotor. In Fig. 1 (b) is shown such a rotor with symmetrical dimensions.

The unbalanced mass, assumed for convenience to have a certain location and value, small in comparison to the mass $M$, is resolved into two component masses, $m_1$ and $m_2$, acting in the balance planes 1 and 2, respectively. These masses are, presumably, unequal in size, and are displaced from each other with respect to the balance planes by an angle $\phi$ as

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represented in Fig. 1 (c). In Fig. 1 (d) is shown an instantaneous position of the rotor system in vibration with two degrees of freedom. The variable distance $x$ represents the displacement of the center of gravity of the body in a lateral direction relative to the position of equilibrium, and the variable angle

TABLE I—NOMENCLATURE

| Symbol | Terminology | Units |
|---|---|---|
| $M, m_1, m_2$ | Mass (W/g) | Poundals |
| $x, d_1, d_2$ | Variables of Position | Inches |
| $\theta$ | Variable Angle | Radians |
| $\phi$ | Unbalance Angle | Degrees |
| $\omega$ | Angular Velocity | Rad. per Sec. |
| $\Psi$ | Relative Angle of Lag | Degrees |
| $R$ | Polar Radius of Gyration | Inches |
| $r$ | Radius of Balance Weights | Inches |
| $a, b$ | Rotor Dimensions | Inches |
| $Q_x$ | Static Unbalance Force | Pounds |
| $Q_\theta$ | Dynamic Unbalance Force at Balance Planes | Pounds |
| $K$ | Flexibility Constant | Lbs. per In. |
| $t$ | Unit of Time | Seconds |
| $k$ | Graphical Constant | Linear |
| $A_1, A_2 \ldots D_2$ | Balance Weights of Equal Mass | Poundals |

$\theta$ the angular displacement of the body with respect to the same axis. The variable distances $d_1$ and $d_2$ are the lateral displacements of the bearing pedestals at the centerline of the shaft. The factor $K$ is the total flexibility or spring constant, in the lateral direction, of the shaft and bearing pedestals. These terms, and others referred to in the discussion, are given in Table I, with their symbols and units.

The equations of motion for the type of mechanical system shown in Fig. 1 (d), may be written in the form of differential equations with two degrees of freedom, the restrictions confining the rotor to lateral and angular motion in the horizontal plane.

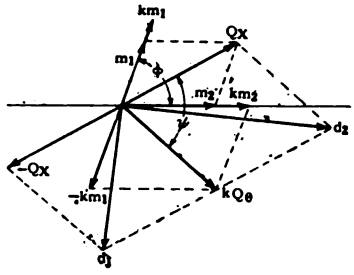


FIG. 2

Considering the potential and kinetic energies of the system the following differential equations can be developed:

$$M\frac{d^2x}{dt^2} + Kx = Q_x \sin \omega t \quad \ldots\ldots (1)$$

$$MR^2\frac{d^2\theta}{dt^2} + Kb^2\theta = a\,Q_\theta \sin(\omega t - \Psi) \quad \ldots\ldots (2)$$

In these equations, the effects of damping are not considered, as the running speed does not approach the critical speed of the rotor, and the absolute angle of lag determined by the degree of damping is immaterial. It is assumed, however, that the relative angle of lag $\Psi$ of the lateral and angular motion takes on a value either zero or 180 deg. depending upon the sign of the graphical constant $k$.

The solution of equation (1) defines the lateral motion of the rotor, and the solution of equation (2) determines the angular motion. Solving (1) and (2), equations (3) and (4), the particular solutions for forced vibration in a steady state, are derived:

$$x = \frac{Q_x}{K - M\omega^2}\sin \omega t \quad \ldots\ldots (3)$$

$$\theta = \frac{a\,Q_\theta}{Kb^2 - MR^2\omega^2}\sin(\omega t + \Psi) \quad \ldots\ldots (4)$$

from which, when the various factors are evaluated, the motion of the rotor with respect to the position of equilibrium is defined.

The resultant force of unbalance, operating in the lateral direction, is represented as $Q_x$. In the above rotor, with unbalance masses $m_1$ and $m_2$, it is equivalent to the vector sum of their resultant centrifugal forces. Equation (5) represents this force function, and it is generally known as the force of the static unbalance.

$$Q_x = r\omega^2\sqrt{m_1^2 + m_2^2 + 2m_1 m_2 \cos\phi} \quad \ldots\ldots (5)$$

The unbalance force $Q_\theta$, creating a moment at the balance planes to cause angular motion, is equiva-

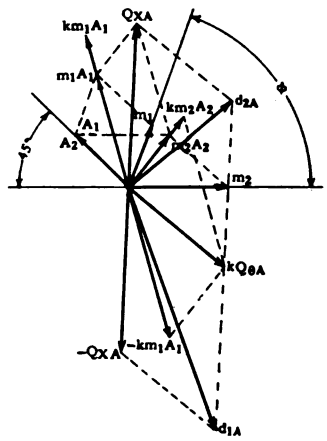


FIG. 3

lent to the vector difference of the centrifugal forces of the unbalance masses. Given in equation (6), this force function is referred to as the force of the dynamic unbalance.

$$Q_\theta = r\omega^2\sqrt{m_1^2 + m_2^2 - 2m_1 m_2 \cos\phi} \quad \ldots\ldots (6)$$

From the schematic diagram, Fig. 1 (d), it is apparent that, at any instant, the positions of the rotor supports are defined by equations (7) and (8).

$$d_1 = b\theta - x \quad \ldots\ldots (7)$$

$$d_2 = b\theta + x \quad \ldots\ldots (8)$$

The action of the static unbalance is to cause the rotor to vibrate with a lateral motion parallel to its centerline; and the dynamic unbalance, to produce an oscillation or angular motion about an axis through the center of gravity at right angles to the centerline. The instantaneous displacement of the bearing pedestals is thus a function of the lateral and angular motions of the rotor. Eqs. (7) and (8) establish this relation; however, since there is a phase difference between the occurrence of the respective maximum amplitudes, it is again necessary to per-

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form the operation with the use of vectors. The vectorial sum and difference of the resultant static and dynamic forces determine the maximum impressed force on each bearing pedestal. Since the deflection of each pedestal depends directly upon the impressed force, the measurement of the maximum amplitude of vibration of the pedestal definitely fixes the maximum unbalance force existing in the rotor at that point. If known unbalances are imposed upon the rotor, and the resulting actions analyzed, the amount and position of the pre-existing unbalances may consequently be brought to light.

*Initial Unbalance*—In explanation of the effects produced upon the unbalanced rotor by proceeding with this method of balancing, consider the rotor with unbalance masses of $m_1$ and $m_2$, as in Fig. 1 (c). It will be assumed that $m_1$ and $m_2$ are known. The vector analysis of the forces which exist in this state of unbalance is given in Fig. 2. The static unbalance force $Q_X$, derived vectorially, is the resultant of the forces as expressed in equation (5); and the dynamic unbalance force $Q_\theta$ is the resultant of the forces expressed in eq. (6). To obtain these resultant forces to the same scale at the pedestals, the dynamic unbalance force is multiplied by the ratio $a:b$, the distance of the center of gravity from the balance planes and the bearing centers respectively.

In the second vector operation here described, another constant involving the rotor dimensions and properties is necessary, a proportionality factor which determines the relation between the lateral and angular displacements of the rotor. From a consideration of eqs. (3) and (4), and eqs. (7) and (8), and including the ratio $a:b$, the proportionality factor $k$, a graphical constant, is found to be equivalent to the spring-mass characteristics of the rotor for the lateral and angular motions, and the relation is expressed as follows:—

$$k = \frac{a^2 (K - M\omega^2)}{K b^2 - M R^2 \omega^2} \quad \text{.....(9)}$$

In the vector diagrams, for convenience, this factor is introduced as a multiplier of all the initial forces which enter into the dynamically unbalanced condition.

In the figures illustrating the action of these unbalance forces, the value of $k$ is given as 1.33. From an inspection of eq. 9, however, it becomes evident that the factor $k$ has a fractional value, and that it may be either positive or negative. The value of $k$ is determined by the ratio of $a/b$, and the degree that the running speed approaches the critical speeds of the two natural frequencies of vibration. The sign of $k$ is positive when the running speed is below the first critical speed ($\omega < K/M$); is negative when the running speed is between the first and second critical speeds ($\omega > K/M$ and $\omega < \sqrt{Kb^2/MR^2}$) and is positive when the running speed is above the second critical speed ($\omega > \sqrt{Kb^2/MR^2}$). The indeterminate condition of $k$ at the critical speeds makes necessary running speeds somewhat removed from them, and it is generally not practical to balance at a running speed between 75 and 120 percent of the absolute critical speeds.

*Unbalance A*—For the second condition of unbalance, the effects of the forces $2A(r\omega^2)$ produced by the two weights, each of mass $A$, attached in the balance planes 1 and 2, indicated by the subscripts, in the same angular position on the rotor, are shown in the vector analysis given graphically in Fig. 3. Carrying through the vector solution, $d_{1A}$ and $d_{2A}$ are found to be proportional to the maximum amplitudes of the bearing pedestals. In this figure, it is observed that the vector of dynamic unbalance $kQ_{\theta A}$ is unchanged from the first condition shown in Fig. 2. This result is axiomatic, and is one of the necessary premises of the problem for, in order to obtain a unique solution, it is essential that only one of the active elements involved be disturbed at a time. Of importance, also, is the fact that the terminal point of this vector bisects

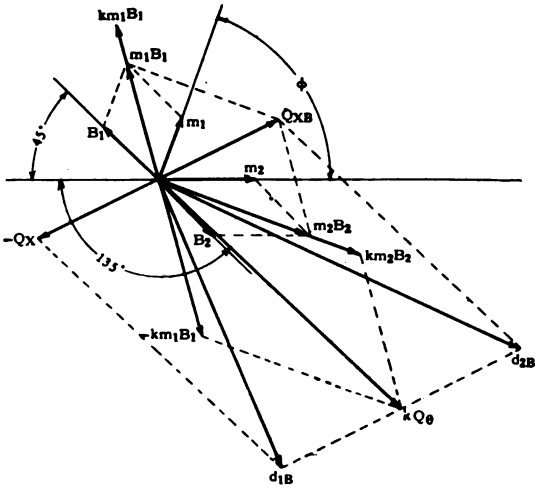

FIG. 4

a line drawn between the vectors $d_{1A}$ and $d_{2A}$ denoting the pedestal amplitudes. The vector $Q_{XA}$ representing the static unbalance has been shifted to the left, indicating that the added unbalance has shifted the center of gravity of the rotor to another position. It is obvious, moreover, that the vector addition of the force $2A$ to the resultant force $Q_X$ in Fig. 2 definitely determines the vector $Q_{XA}$ in Fig. 3, which conception may be established both physically and analytically.

*Unbalance B*—Continuing to Fig. 4, which represents the third condition of unbalance, the added unbalance now being referred to as $B_1$ and $B_2$ when the added weight in balance plane 2 has been shifted 180 degrees, the static unbalance force vector $Q_{XB}$ occupies the same position as the vector $Q_X$ in Fig. 2. It is also to be observed that the lines joining $d_1$ and $d_2$ in Fig. 2, and $d_{1B}$ and $d_{2B}$ in Fig. 4 are parallel, of equal length, and each is bisected by the terminal point of the vector representing the dynamic unbalance, $k\,Q_\theta$ and $k\,Q_{\theta B}$ respectively.

*Unbalance C*—In the fourth condition, the added weights, noted as $C_1$ and $C_2$ in this case, are both displaced 180 degrees from the initial positions shown

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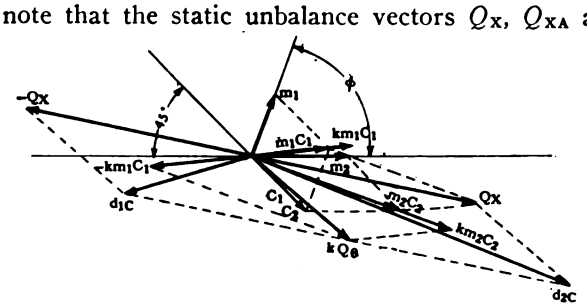
in Fig. 3, and the vector diagrams are given in Fig. 5. The dynamic vector $kQ_{\theta C}$ coincides with those given in Figs. 2 and 3, and the terminal point is the midpoint of the line joining the pedestal deflection vectors $d_{1C}$ and $d_{2C}$. The static unbalance vector is over to the right of the original $Q_X$, and is displaced an amount equal to the addition of the vector component having twice the value of $C$.

*Unbalance D*—In the fifth and last condition of unbalance, Fig. 6 the weights $D_1$ and $D_2$ are placed 90 degrees from the initial positions in the second run. The purpose of this trial run is to establish the locations of the holes in the balance rings relative to the vector diagrams. The dynamic unbalance vector $k\,Q_{\theta D}$ coincides with the previously drawn dynamic unbalance vectors terminating at $k\,Q_\theta$.

If the resulting vectors of the five conditions are combined in one diagram as in Fig. 7, all the forces and displacement functions are correlated in the manner which would be anticipated from the foregoing discussion. Thus the static unbalance vector $Q_{XD}$ from Fig. 6 is seen in Fig. 7 to terminate on a circle drawn with point $Q_X$ as a center and with a radius equal to the lengths of the lines $Q_{XA}Q_X$ and $Q_{XC}Q_X$. The radius line $Q_{XD}$ is at right angles to the diametral line $Q_{XA}Q_{XC}$. Allowing the circle to represent the balancing rings, trial run $D$ determines in which semicircle the 90 deg. unbalance was placed, and thus definitely locates all vector positions. The vectors $d_{1D}$ and $d_{2D}$, representing the pedestal amplitudes, are not geometrically tied in with the other amplitude vectors, except that the midpoint of the line between them is at the terminus of the vector $kQ_{\theta D}$.

From Fig. 7 some interesting and valuable relations are determined. The lines $d_1$, $d_2$ and $d_{1B}$, $d_{2B}$ are parallel and of equal length; the midpoints of lines $d_1d_2$, $d_{1A}d_{2A}$, $d_{1C}d_{2C}$ and $d_{1D}d_{2D}$ all fall at the terminus of $kQ_\theta$. The end points of $d_1d_2$, $d_{1A}d_{2A}$, $d_{1B}d_{2B}$ and and $d_{1C}d_{2C}$ fall on two parallel lines. It is important to note that the static unbalance vectors $Q_X$, $Q_{XA}$ and




FGI. 5

$Q_{XC}$ are parallel to, and equal to one-half the length of the lines $d_1d_2$, $d_{1A}d_{2A}$ and $d_{1C}d_{2C}$, respectively. The line joining $Q_{XA}$ and $Q_{XC}$ is bisected by the terminal of the vector $Q_X$ and the line $Q_{XD}Q_X$, equal to one-half its length, is at right angles to it. From the relations of these vectors established by the five test runs the unknown unbalance can be determined.

In Fig. 8, all these force and displacement vectors are shown transposed from Fig. 7. Of course, the unbalance force vectors have been considered fixed with respect to one another, while they are rotating in space with the rotor at the angular velocity of $\omega$ radians per second. Thus the resultant displacements $d_1$ and $d_2$ are considered maximum when the greatest lateral deflections occur at different relative positions. Circles, drawn with point 0 as the center and radii equal to the

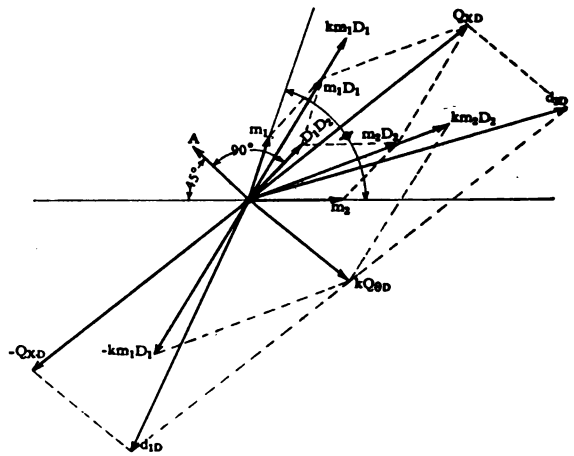



FIG. 6

length of the displacement vectors, indicate the end points of these vectors, from which loci of points it is possible to solve for the positions of the resultant forces.

## SOLUTION FOR INITIAL UNBALANCE

Let the five unbalance trials on the rotor illustrated above give maximum pedestal deflections of $d_1$, $d_2$, $d_{1A}$.....$d_{2D}$ from vibration readings taken for each trial. These readings, and the size and position of the added weights, constitute the known data of the problem.

1—Since the directions of the deflection vectors are quite unknown, it is first necessary to locate their loci by drawing circles accurately, and to fairly large scale, as in Fig. 8, with radii corresponding to the maximum amplitudes in each of the ten trial measurements. These are lettered $d_1$, $d_2$, $d_{1A}$.....$d_{2D}$, corresponding to the deflections they represent.

2—The first problem is to locate $kQ_\theta$. This is done by trial but the process can be greatly simplified by limiting its position as far as possible. Inasmuch as no point on any circle has been located the locus of $kQ_\theta$ can be limited to any radius, preferably the vertical one above the center (see Fig. 10).

3—There are four lines, direction as yet unknown, $d_1d_2$, $d_{1A}d_{2A}$, $d_{1C}d_{2C}$, $d_{1D}d_{2D}$, terminating on the corresponding deflection circles, which are bisected by $kQ_\theta$; Each of these bisections has a larger and a smaller limit on the above locus of $kQ_\theta$. Let $x$ = the larger and $y$ = the smaller limit.

$$\textit{The larger limit} = \frac{x+y}{2}$$

$$\textit{The smaller limit} = \frac{x+y}{2} - y$$

Both limits occur, for any of these four lines, when that line coincides with the locus line of $kQ_\theta$. For

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example, substituting $d_1$ and $d_2$ for $x$ and $y$, the limits of the middle of line $d_1d_2$ are readily located. Since all these lines must pass through $kQ_\theta$, the locus of this point is limited to the range on the locus line between the shortest of the four larger limits and the longest of the four smaller limits.

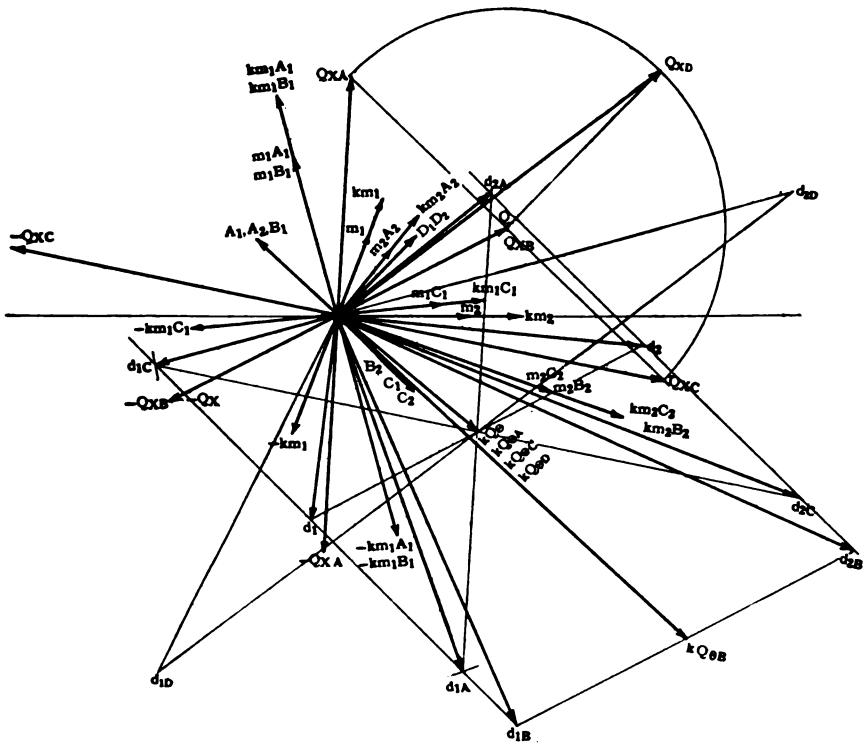


FIG. 7

4—Through any point on the limited locus just determined, two lines $d_1d_2$, two lines $d_{1A}d_{2A}$, etc., can be drawn, with their ends on the corresponding circles, and bisected by the point representing, for trial, $kQ_\theta$; one sloping up to the right, and the other sloping down to the right by the same angle. Using both gives two complete solutions*, for check. Since in any one case, it is impossible as yet to know which slope to choose, it is just as easy to draw both. This is apt to simplify subsequent operations.

5—There is no way of determining the point on the limited locus which actually corresponds to $kQ_\theta$ except by trial. For intial trials it is usually easier tentatively to locate $kQ_\theta$ at the upper and lower limits and the half-way point of the locus. Lines corresponding to the conditions specified under 4 are then drawn through each of these points, preferably using pencils of different colors for each of the assumed points.

6—The determining conditions to tell when point $kQ_\theta$ has by trial been accurately located are that points $d_1$, $d_{1A}$, $d_{1B}$ and $d_{1C}$ all fall on one straight line; $d_2$, $d_{2A}$, $d_{2B}$ and $d_{2C}$ all fall on another straight line; that these two straight lines are parallel; that lines $d_{1A}d_{1C}$ and $d_{2A}d_{2C}$ are bisected respectively by $d_1$ and $d_2$; and that $d_{1B}d_{2B}$ is equal and parallel to $d_1d_2$, although $d_{1B}d_{2B}$ does not pass through $kQ_\theta$.

7—The initial trial positions of $kQ$, when tested by the conditions imposed in paragraph 6 will indicate quite closely where the next trial position of $kQ_\theta$ should be selected.

8—Additional trial points for $kQ_\theta$ are selected until one is found which meets all the conditions of paragraph 6 with a reasonable degree of accuracy. It is generally found in the above construction that one or more of the circles do not have the exact radii to conform in the required manner, and that slight adjustments are necessary. This results from individual small errors in the reading of the amplitudes. Slight adjustments of a few of the circles within the limits of observational errors are at times necessary, and these adjustments may be carried back to the selection of the point $kQ_\theta$ if desired and the errors distributed over the whole construction. Such slight discrepancies are not serious, for with the several checks and the exercise of compensations, the final errors are within allowable limits.

An alternative to this construction is to find by trial two lines parallel in direction and equal in length, with their end points on the circles of radii $d_1$ and $d_2$, and $d_{1B}$ and $d_{2B}$, respectively. However, this is not always possible, for under certain conditions, these radii are nearly the same. To present a better check in such a case, it is often desirable that after trial run $B$ is made, the maximum amplitudes be compared with the original run, and if the variation is small, the dynamic unbalance weights be doubled or tripled, and the test repeated. The dynamic unbalance readings of amplitude will thus become larger, and compare more favorably with the static unbalance readings with re-

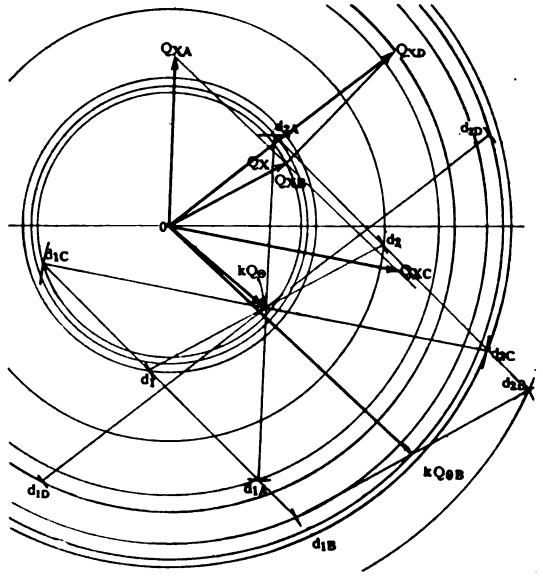


FIG. 8

*These are duplicate, except reversed from right to left.

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gard to accuracy in the diagramatic construction. The midpoint of the line $d_1d_2$ would determine the point $kQ_\theta$ as before. Point $kQ_{\theta B}$ is at the midpoint of $d_{1B}d_{2B}$.

It has been previously noted that the vectors of amplitude are derived by adding and subtracting the vectors of static unbalance to the vectors of dynamic unbalance; thus, since the lines joining the vectors of amplitude, with their midpoints at $kQ_\theta$ and $kQ_{\theta B}$, are derived as above, the static unbalance vectors $Q_X$, $Q_{XA}$ .....$Q_{XD}$ are drawn parallel and equal to one-half the length of the lines $d_1d_2$, $d_{1A}d_{2A}$.....$d_{1D}d_{2D}$, respectively. In Fig. 8, these vectors are drawn from the center of the circles. This is not necessary, as the center of these force vectors may remain at point $kQ_\theta$ for simplification. In a practical example, as shown in Fig. 10, the drawing is greatly simplified by considering $kQ_\theta$ as the center of the static force vectors, because in this case point $Q_X$ coincides with point $d_2$ (on this diagram the letters $d$ for deflection are omitted for simplicity, the point being designated solely by the subnumber); similarly $Q_{XA}$ corresponds to $2A$, $Q_{XC}$ corresponds to $2C$ and $Q_{XD}$ corresponds to $2D$.

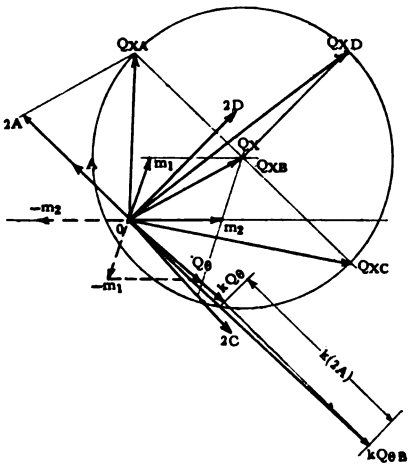


FIG. 9

A simplified sketch of the forces in Fig. 8 is given in Fig. 9. Since the static unbalance force added ($2A$ in value) produces a displacement to $Q_{XA}$ from the original unbalance at $Q_X$ in the second trial; and the same unbalance on the other side of the rotor produces a displacement $Q_{XC}$ in the fourth trial; then in the third trial, as has been shown, a dynamic unbalance of the same amount added to $kQ_\theta$ will produce a dynamic displacement to $kQ_{\theta B}$. Dividing the displacement from $kQ_\theta$ to $kQ_{\theta B}$ by the displacement from $Q_X$ to either $Q_{XA}$ or $Q_{XC}$ (each of which displacements equals $2A$*) determines the value of the factor $k$ (by definition). The vectors $Q_X$ and $kQ_\theta/k$ or $Q_\theta$ are then vectors of the sum and difference of the unknown unbalance force vectors $m_1$ and $m_2$.

The component vectors of these forces are located by bisecting the line joining the points $Q_X$ and $Q_\theta$, thus determining the end point of the unbalance $m_2$; and the unbalance $m_1$ is therefore parallel to this line and equal to one-half its length. From a comparison of the lengths of the vectors $m_1$ and $m_2$ with the vector $A$, the mass of which is known, the masses of the unknown unbalances are derived. The position on the rotor of $m_1$ and $m_2$ is determined by drawing a circle representing the balancing rings with $Q_X$ as center through $Q_{XA}$, $Q_{XC}$, and $Q_{XD}$. The positions on the rotor at which weights $A$, $C$, and $D$ were placed correspond to points on the circle $Q_{XA}$, $Q_{XC}$ and $Q_{XD}$. Transferring vectors $m_1$ and $m_2$ to the center $Q_X$ of this circle, fixes their position, with reference to the balancing positions on the rotor. Thus the solution for the size and position of the components of the original rotor unbalance is obtained.

The rotor is balanced by attaching weights to counteract exactly the unbalance masses $m_1$ and $m_2$. A weight, equivalent in mass to $m_1$, is placed in balance plane 1 exactly 180 degrees from the vector position of $m_1$ determined from the diagram Fig. 9. When it is not possible to attach the correction weights at the exact positions indicated on the diagram, components of the vector unbalances are derived, and two or more weights are attached at convenient locations to give exactly the same effect. Another weight, equivalent in mass to $m_2$, is fixed in balance plane 2 in the same manner. The rotor, in this condition, should operate free from vibration; and if the amplitude readings are correct and the graphical solutions carefully made, such will be the case. However, if a slight vibration is evident, the data and the diagram should be checked thoroughly to make certain that no discrepancies are involved in the solution. It is possible that some part of the data is questionable, and check runs should be made to remove this possibility. Balancing by trial to remove a residual unbalance is of little use, but refinement of the data and an accurate check of the vector diagram are of great importance. If accuracy is maintained throughout, there will be no necessity for further balancing in most cases.

### EXAMPLE OF BALANCING

Applying this method of balancing to a synchronous condenser of 5000 kv-a capacity, with an exciter drive, operating at 900 r.p.m., the data given in Table II was obtained.

The vector solution of the original unbalance for this machine is given in Fig. 10. The circles corresponding to the deflections are drawn and lettered, and point $kQ_\theta$ is determined and checked as previously described. In this case, for simplicity, point $kQ_\theta$ was selected as the center for the static unbalance vectors, locating $Q_{XA}$ at point $2A$, etc., without transferring the vectors. As the distances from point 2 to either $2A$ or $2C$ or from 1 to either $1A$ or $1C$ all correspond to twice the trial balance weights used (equal $2 \times 37.5$ oz.), the scale for vectors $m_1$ and $m_2$ are thus determined.

A complete circle is then drawn with $Q_X$ as the

*See last sentence under heading *Unbalance A*.

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center through points $Q_{XA}$, $Q_{XD}$ (equals 2D) and $Q_{XC}$ representing the balance ring on the end of the rotor designated as 2 in Table II. Thus $Q_{XA}$ corresponds to balance ring location 13, $Q_{XC}$ corresponds to balance ring location 3 and $Q_{XD}$ corresponds to balance ring location 18, as determined from the test data. From the known position of these three points the position of the other balance ring locations are determined.

TABLE II—DATA FROM BALANCING TEST

| Trial Run | Balancing Plane | Diagram Notation | Balancing Weights (Ounces) | Balance Ring Location | Maximum Amplitudes (1-1000 in.) |
|---|---|---|---|---|---|
| Initial | 1 | 1 | None | .. | 3.0 |
| Initial | 2 | 2 | None | .. | 5.0 |
| A | 1 | 1A | 37.5 | 13 | 8.0 |
| A | 2 | 2A | 37.5 | 13 | 10.4 |
| B | 1 | 1B | 37.5 | 3 | 2.0 |
| B | 2 | 2B | 37.5 | 13 | 5.5 |
| C | 1 | 1C | 37.5 | 3 | 13.0 |
| C | 2 | 2C | 37.5 | 3 | 12.5 |
| D | 1 | 1D | 37.5 | 18 | 12.6 |
| D | 2 | 2D | 37.5 | 18 | 5.7 |

It will be noted that nothing in the method of locating the static unbalance vectors indicates that $Q_{XA}$ should coincide with $2A$ rather than $1A$. As a matter of fact this makes no difference. If $Q_X$ be considered as located at point 1 instead of 2, $Q_{XA}$ at point 1A instead of at point 2A, etc., another circle will result, from which the locations of the point on the balance ring can be determined, being sure to locate the position of the balance ring according to the balance plane which is being considered. Either circle may be drawn with identical ultimate results so that, of course, there is no object in drawing both. One represents the balance rings as viewed from one end of the rotor and the other represents the same balance rings as viewed from the other end. It should be remembered that the balance points on the rotor will appear to be numbered in clockwise direction from one end and counterclockwise direction from the other end. Hence, if both circles are put in they will be numbered in opposite directions.

The value of $k$ for this speed and rotor mounting was found to be (1/7.7). In this particular case, instead of solving for vectors $m_1$ and $m_2$ and then transferring them, the vectors $Q_0$ and $Q_X$ were transferred to $QX$, the center of the balance ring circle, and the values of $m_1$ and $m_2$ then determined. This gives the location of $m_1$ and $m_2$ with reference to the balance rings directly without subsequent transfer.

The unbalance in balance plane 1 was 87 ounces, and in balance plane 2, 95 ounces. In balance plane 1, 87 ounces was placed on balance plug No. 9, this being close enough to the correct position, and in balance plane 2, 57 ounces were placed on balance plug No. 18, and 39 ounces on balance plug No. 19. As a final check, the rotor was operated in this condition, and the amplitudes recorded were 0.0005 and 0.00075 inches at ends 1 and 2 respectively. These amplitudes are well within the limits defined for smooth operation, and appear to justify the practical adoption of this method of balancing.

There are many factors which might cause vibration in machines other than unbalance. Among these are the displacement of the center of gravity of a rotor when its temperature is changed; eccentricity of the journals; misalignment of the bearings or couplings; warped shafts; shifting elements in the rotor body; and resonant (critical speed) conditions in the immediate structure or the supporting foundations. Unbalance, however, remains the most common cause of vibration, and it is often difficult to prove that the disturbance is not due to unbalance, even when some other factor is responsible. Erratic results are obtained when attempts are made to balance a rotor under these conditions, although with the usual methods of balancing, recognition of this discrepancy is possible only after an indefinite series of trials. With the scientific method of balancing as here given, when a vibrational disturbance cannot be corrected by balancing, it is impossible to obtain a graphical solution. A negative result is

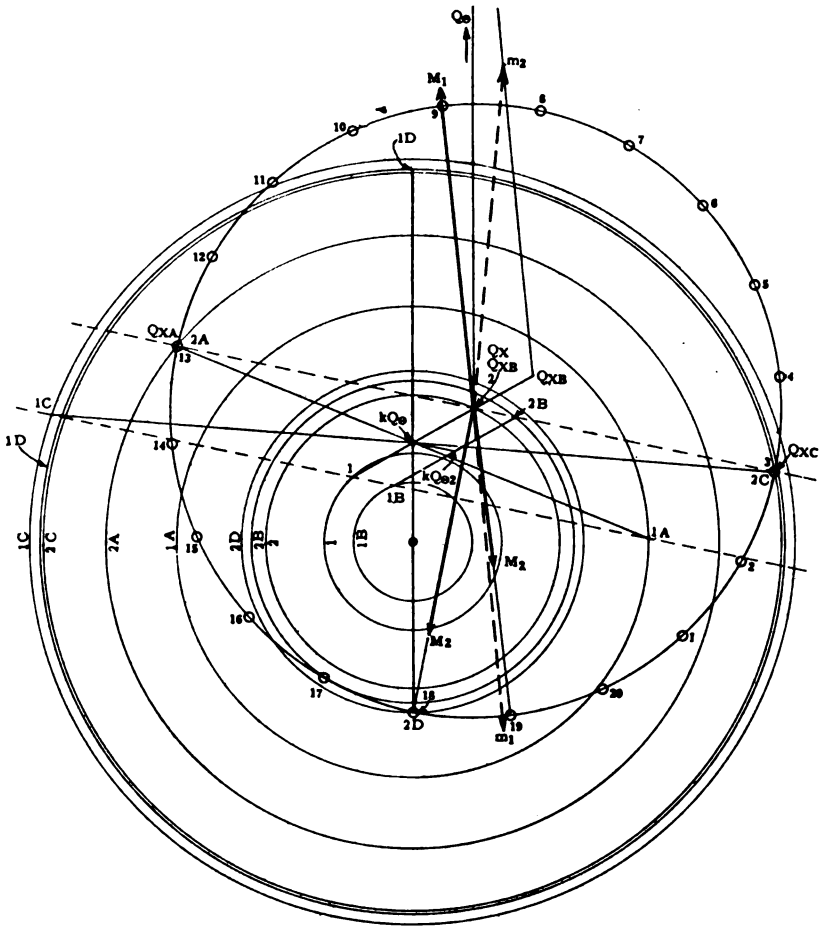


FIG. 10

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just as valuable, in such a case, as one that is positive in the opposite case. The utmost precaution must, however, be observed before reaching the conclusion that a balance is not obtainable by the previously described method. But with some experience in the application of this method, negative results are as dependable as positive ones.

The advantages of the scientific method of field balancing are threefold:—it is straight-forward, requiring the machine to be withheld from service only for sufficient time to make five balancing runs in succession, with but a short time for graphical calculation and final balancing; it is simple, for only a few physical measurements are necessary, and the calculation deal merely with the addition and subtraction of vectors; it is accurate, for the errors are compensating, and the final solution is within the limits of the errors of the observations.

The method is useful in that it attacks a critical problem in a practical way. The experience obtained from the careful observance of the actions of rotors in vibration, where definite balancing steps are followed, and records of the results are catalogued, becomes very helpful in the solution of vibration problems of more complex nature. Its use is not limited to the expert, but it becomes a tool in the hands of the operator. The designer also becomes aware that the vibration problem is much more susceptible to solution when the type of machine is conventional. Moreover, with the simplification of field balancing methods, an incentive will be given for further investigation of the many factors which cause vibrational phenomena in the operation of rotors other than pure unbalance.

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# Surge Voltages Produced by Direct-Current, Air, Circuit Interrupters

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THE overvoltages which develop when rupturing a direct-current circuit form an important consideration in the design and also in the application of various kinds of switches. These voltages may vary from twice to several times normal; and though of short duration, the frequency of their occurrence, in many applications, places a severe duty on the insulation. Instances are also known in which switching surges have caused commutator machines to flash. Because of the seriousness which this seemingly minor phenomenon sometimes assumes, and the comparative ease with which difficulties may often be overcome, the subject is worthy of investigation. The effects of rupturing direct-current circuits with air switches will be treated first, from the standpoint of voltage breakdown within portions of circuits and to ground.

Direct-current transient phenomena are all based on the relation that the resistance drop in a circuit, plus its inductance times the rate of change of current, are equal to the impressed voltage. If a circuit is ruptured by opening a switch, the voltage across the switch must be added to the above, opposite in direction to the impressed voltage. If the circuit contained only resistance, the rupture would be very simple; the current would halt in zero time with no overvoltage or arc in the switch. When the circuit contains inductance, as in the practical case, some time is required to bring the current to zero. The energy stored magnetically must be dissipated in some manner, usually by means of the arc formed in the switch. Actually the total energy to be dissipated must be greater than the stored energy because, during the time required for the process, additional energy is supplied by the power source. The total energy may be expressed as the product of the instantaneous current, switch voltage and the summation of the arcing time. If the time is quite small, the voltage may be very large. In other words, the rate of change of current times the inductance will become larger as the rupturing time becomes

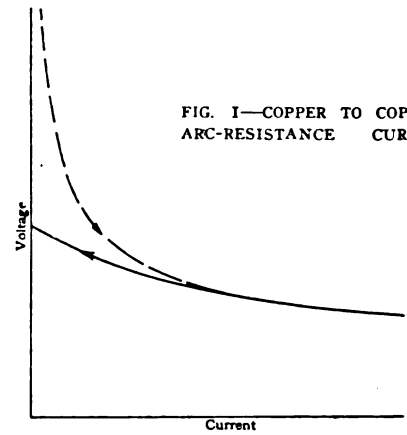


FIG. I—COPPER TO COPPER ARC-RESISTANCE CURVES

smaller. The price to be paid for low arc energy is therefore a high voltage.

The manner in which the current decreases during rupture is dictated entirely by the characteristics of the arc, that is, its resistance. A typical curve of arc current and voltage is shown in Fig. 1. The dash curve is a static characteristic given by points obtained from a stable arc. The solid curve or transient characteristic results from obtaining the voltage while decreasing the current, and lies below the static curve because the temperature of the electrodes is higher at the lower

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current values. The current decreases more rapidly than the electrodes can cool. It is therefore, the transient curve which must be used in switch calculations.

When a switch is first opened during a heavy overload, the arc forms with the overload current and at a low voltage. Then both change along the curve until

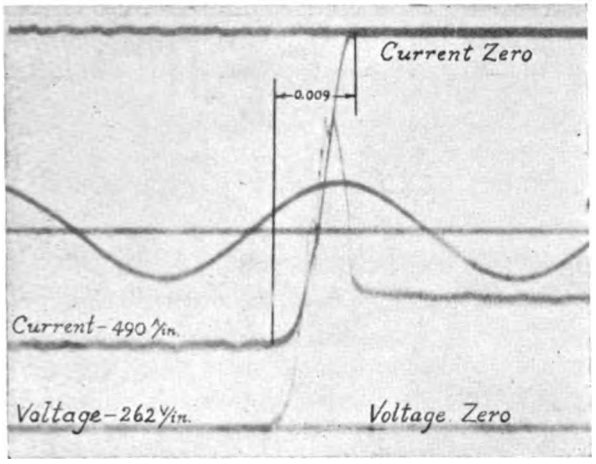


FIG. 2—OSCILLOGRAM SHOWING THE VOLTAGE SURGE CAUSED BY INTERRUPTING A HEAVY CURRENT

final rupture, at which time the highest voltage is present. Fig. 2 is an oscillographic record of the arc voltage and current during rupture. The slope of the current curve has a tendency to increase as the current becomes lessened, because of the property of most switches of blowing the arc to a greater length in order to reduce rupturing time.

The curves, Fig. 1, are for a constant arc length. Actually the arc length increases rapidly. In Fig. 3 several curves are shown for different arc lengths. The switch characteristic travels from one curve to the next larger in the family in a fashion which allows the switch characteristic to have almost any shape. The switch has inherent properties which determine the shape of the curves. It is well to examine them because the final switch voltage depends on these factors.

Practically all air switches have some form of blowout coil to lengthen the arc and hence increase its resistance. One of the problems in building a switch

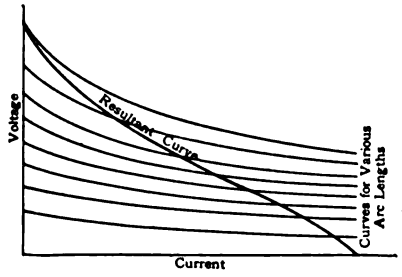


FIG. 3—VARIABLE ARC LENGTH RESISTANCE CURVES

is to cause the arc, which forms initially on the contacts, to begin its motion onto the arc horns. The arc has a tendency to remain of short length between the contacts because it forms with a hot crater at the cathode. Some time is lost, therefore, during which the arc remains at a low voltage. When motion does start the lengthening is rapid, and the result is a curve similar to *A*, Fig. 4. Such a switch gives a high final voltage. The characteristic at *B* is to be preferred, and may be obtained by rapid separation speed of the contacts and a strong, confined blowout. The line $E - IR$ in the figure is the applied voltage less the $IR$ drop of a circuit which the switch may be opening. The area between this line and the switch characteristic is nearly inversely proportional to the energy dissipated in the switch, which explains that the switch having the characteristic *B* has a minimum overvoltage with the minimum energy and rupturing time.

The switch overvoltage will vary with rupturing time and circuit inductance, but peculiarly enough, is often nearly twice the normal applied voltage in the case of contactors except for high inductances. The reason for this constancy is that the basic structure of a contactor tends to keep the product of inductance and rate of current change constant, automatically taking more time for the rupture if the stored energy is high. When opening field circuits or large coils the voltage may be four or five times normal, but for gen-

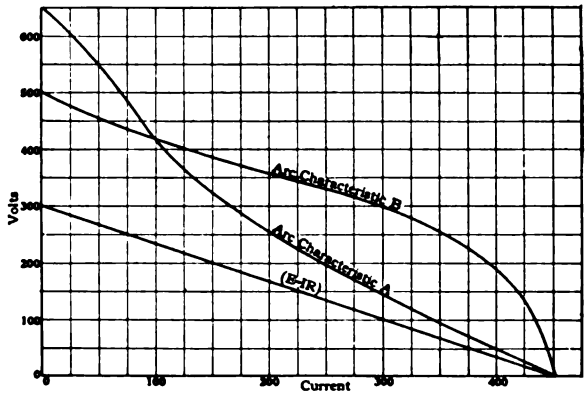


FIG. 4—SWITCH CHARACTERISTIC CURVES

eral power circuits the voltage is about the magnitude of twice normal.

Another fundamental of switch operation is that any combination with the circuit or operating condition which enables stored energy to be dissipated elsewhere than in the switch will reduce the peak voltages. Circuits containing mutual inductance are easily ruptured because the transient currents induced in the secondary circuit dissipate a portion of the energy. There are known devices for reducing switch energy and consequently voltage. The most common of these are shunting a switch with a resistance which is later opened by a second switch; and shunting the load with a proper resistance. Either, properly done, will almost remove excessive voltages. In case the load consists of rotating machinery, the function of the switch is to disconnect two voltages, that generated and the counter e.m.f. This function may be performed with low overvoltages. Switch voltages are always higher with machines blocked, than when they are running.

From these fundamental concepts, it is possible to proceed to the study of a few typical circuits in order to determine the effect of surge voltages. It is obvious

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that the voltage across the load in a simple circuit containing only a power source, a load, and a switch will be the supply voltage minus the switch voltage, and since the switch voltage is the larger, the load voltage will be negative. In Fig. 5 a circuit is shown containing two motors in series. The switch may be located at 1, 2 or 3. The surge voltage across the load is independent of switch location, and the switch will be assumed to give twice normal voltage. The load voltage will equal the supply voltage, provided the motor field structures are well laminated, so that their counter e.m.f. falls rapidly to zero.

The voltages to ground, however, will vary with the switch position. The first three voltage diagrams show the effect of opening any of the three switches, assuming that the negative side of the generator is grounded. The voltage at *a* must be supply voltage. When switch 1 is opened, in proceeding from *b* to *c*, the voltage will increase; and also from *d* to *e* there will be an increase due to the inductive $L$ $(di/dt)$ voltage. The switch voltage from *e* to *f* reduces the circuit voltage to ground potential. These voltages are, of course, the transients at the peak of the voltage surge. Curve 2 of Fig. 5 shows the voltages if switch 2 is opened; and curve 3, if the third switch is opened. In case the supply potential was 250 volts, the maximum voltage to ground

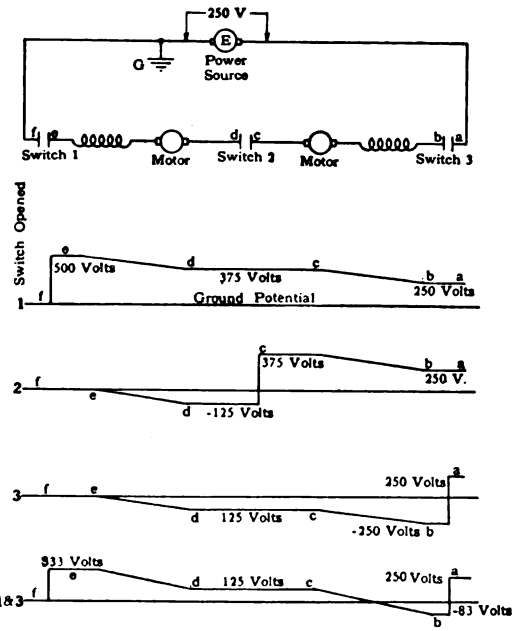


FIG. 5—THE EFFECT OF SWITCH POSITION ON VOLTAGE SURGES

would be 500 volts in case 1 but only 250 volts in case 3. The switch at 3, therefore, would be the most desirable location.

The *IR* drops of the circuit were neglected because at the final instant of opening, the current would be zero, and these drops would be zero. If the motors were separately excited, their voltage should be taken into account, which would alter the potentials to ground, but would not affect the switch placing for minimum surge voltage.

The next logical question is,—what will be the magnitude of surges if two of the switches, 1 and 3, for example, open simultaneously. Two switches, operating in series will rupture a circuit more rapidly than one, and the sum of both switch voltages will be greater than one. The sum will be less than twice the previously assumed value of twice normal voltage, however, because the rupturing time will not be halved. The resultant voltage may be about two-thirds the actual sum of the switch voltage; i.e. of the order of eight-thirds normal. A transient voltage diagram under this condition is also shown in Fig. 5.

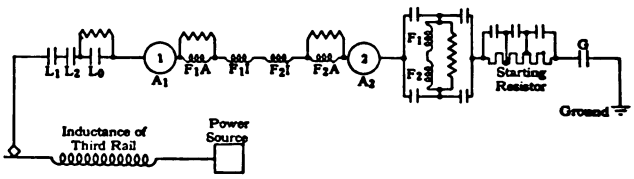


FIG. 6—A SCHEMATIC MOTOR CIRCUIT ON A LOCOMOTIVE

One of the most interesting circuits for analysis is a third-rail railway system, because the third-rail inductance plays a striking part in the phenomena. Such a circuit is shown in Fig. 6. The load may consist of a locomotive having four series motors and the usual series parallel arrangement. One of the two parallel circuits, each consisting of two motors permanently in series, is shown in the diagram. It is obvious that the highest voltages across individual units of the circuit will occur if the circuit is ruptured when the locomotive is near a substation, because there the entire switch voltage must appear across the locomotive apparatus with no voltage drop between the locomotive and the substation. It may be seen also that the voltages across units of the circuit will be the same regardless of which switch is opened first; but will be the greater if more than one switch is opened—a condition which is possible. The most desirable method of rupturing the circuit is to open the resistance switch $L_0$ first, followed by a line switch.

With respect to the voltages to ground, it will be assumed first that the locomotive is located near a substation. If the motors are in the parallel combination, one parallel of which is shown in Fig. 6, the circuit containing the motors numbered 1 and 2 may be opened by either the line switch or the switch marked *G*. If the latter switch is opened, the voltage to ground of the adjacent motor field will be about twice normal, and this voltage will diminish in passing along the circuit to the third rail. If the line switch is opened, however, the potential to ground at the point nearest this switch will be the maximum in the circuit, but will only be normal voltage, and will decrease in going along the circuit toward ground. As before, opening switches simultaneously will give rise to higher surge voltages.

In case the locomotive is not at a substation, most of the surge voltage would appear across the third rail. Opening the switch *G* would give possibly a little higher voltage to ground, also this voltage would be at nearly the same maximum throughout the locomotive;

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hence the most undesirable condition would be obtained. When opening the line switch, conditions are better at a distance from a substation, because practically the entire locomotive will have nearly zero potential to ground. From the above it follows that a practical solution to surge difficulties may be obtained by properly interlocking switches, in order that the ones causing the least disturbance will open first.

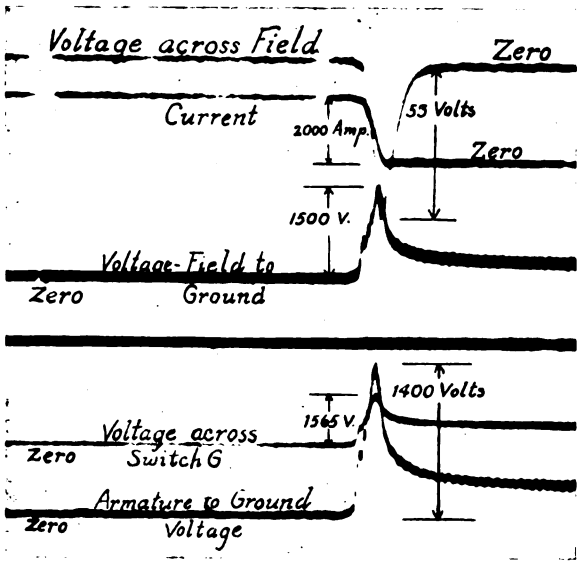


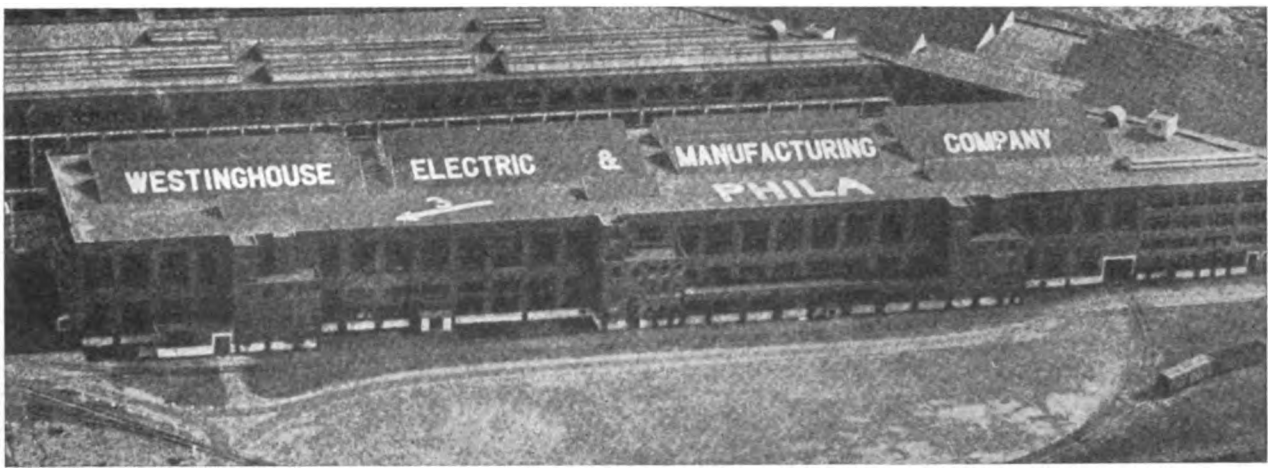

FIG. 7—OSCILLOGRAM SHOWING EFFECT OF OPENING THE POWER CIRCUIT OF A LOCOMOTIVE AT STANDSTILL

As before, conditions are less severe with the locomotive running than if the current is broken with it practically stationary. The generated voltage of a series machine disappears very rapidly when it is disconnected, but because of damping currents in the frame a voltage of half normal is often present at the final rupturing instant. Fig. 7 shows an oscillogram taken under conditions similar to those of Fig. 6. The locomotive was blocked, some distance from the substation, and the switch *G* was opened. The third rail voltage was 600, and it can be seen that surges of more than double this value were obtained from the field and armature of No. 2 motor to ground.

It is from such considerations as these that the best arrangement of circuits and switches may be obtained. Trouble due to such surges is frequent, and often the fault is assumed due to other conditions. The exact effect of such surges on insulation is not determined, though experience with failures serves to condemn them sufficiently. The commutator machine is a severe sufferer, because the surge voltage plus the high voltage between commutator bars at points of commutation places undue strain on the insulating mica. The sum of these voltages is sufficient at times to cause motor flashing. Many instances have been observed where compressor motors on a third-rail system would flash when the main-motor circuits were opened. It is not uncommon for third-rail voltages to reach four times normal or higher during switching, because of the excessive inductance in the rail.

Another switch phenomenon which throws particular hardship on insulation is constant re-ignition of the arc within the switch. This re-ignition is due to the arc re-striking in the contacts after having been blown out, and is difficult to avoid. The result is that a high voltage of high frequency is impressed on the insulation for a large portion of the total switching time.

A number of solutions have been mentioned, all of which depend in principle upon less rapid dissipation of energy or providing a number of outlets for the stored energy. Lightning arresters form a further very effective means, when they can be used to dissipate circuit energy when circuit voltages become abnormal. Proper selection of switches, their proper placing and interlocking within the circuit, and the use of special means such as resistance switches or arresters when justified, will meet almost any switching surge problem with a sure solution.




On the air-mail route between New York and Atlanta an airport directional sign has been installed on the roof of the South Philadelphia Works of the Westinghouse Electric & Mfg. Co., four miles from Chester, Pa., and three miles from the airport. At night the sign is illuminated with floodlight projectors equipped with 1000 watt lamps, which provide illumination six foot-candles in intensity. The sign is visible in every detail at a 2000 ft. elevation and at time of good visibility can be seen from 6000 feet.

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# Methods of Testing Electrical Apparatus

## XXIX—Three-Phase Transformers

The tests to be made on three-phase transformers are similar to those for the corresponding types of single-phase transformers.

### RATIO

All general instructions and precautions given for the ratio test on single-phase transformers[1] must be observed when making this test on three-phase units. The usual and most convenient method of making the ratio test of a three-phase transformer is to test each phase separately. The test is carried on as for a single-phase transformer of the corresponding type. If a case should arise wherein the high-voltage windings are connected in star and the neutral point is inaccessible, then three-phase voltage should be applied and the pro-

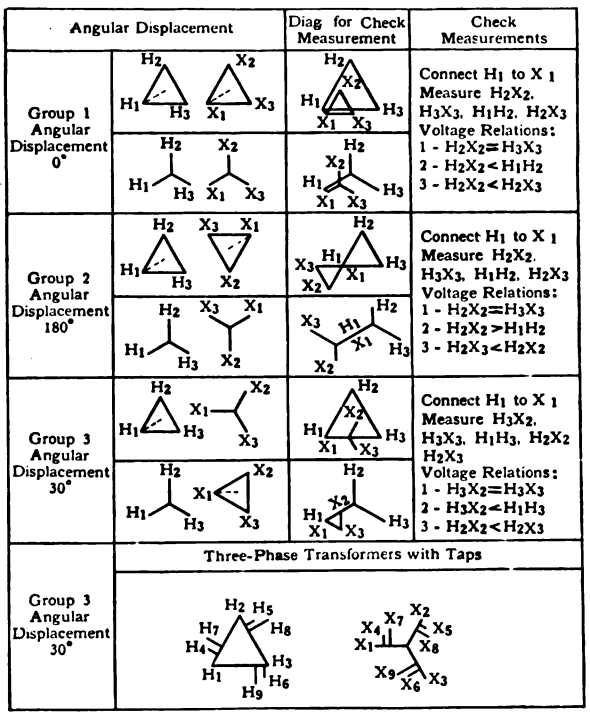


FIG. 128—TRANSFORMER LEAD MARKINGS AND VOLTAGE VECTOR DIAGRAMS FOR THREE-PHASE TRANSFORMER CONNECTIONS

cedure carried on in a manner similar to that described for the single-phase, core-type transformer[1].

### POLARITY AND ANGULAR DISPLACEMENT

As a general rule, all phases of a three-phase transformer have the same relative polarity (expressed in terms of single-phase polarity); i.e., if the polarity of one phase is subtractive, the polarity of the second and third phase also will be subtractive; or if the polarity of one phase is additive, the polarity of the second and third phase also will be additive.

The three-phase polarity, however, is dependent upon the interphase connections and the relative connections of the respective high-voltage and low-voltage outlet leads to the full phase windings, as well as the polarity of the separate phases. The three-phase polarity is denoted by definite markings of the outlet leads with reference to voltage vector diagrams which indicate the relative phase rotation and the angular displacement between the high-voltage and low-voltage windings.

The three high-voltage leads and the three low-voltage leads, which connect to the full phase windings, are marked $H_1$, $H_2$, $H_3$ and $X_1$, $X_2$, $X_3$. The full phase winding of a tertiary winding is marked $Y_1$, $Y_2$, $Y_3$. A neutral lead (not a 50 percent tap for starting purposes) should be marked with the proper letter followed by $_0$; i.e., $H_0$, $X_0$. The markings are so applied that, with the phase sequence of voltage on the high-voltage side in the time order $H_1$, $H_2$, $H_3$, it is in the

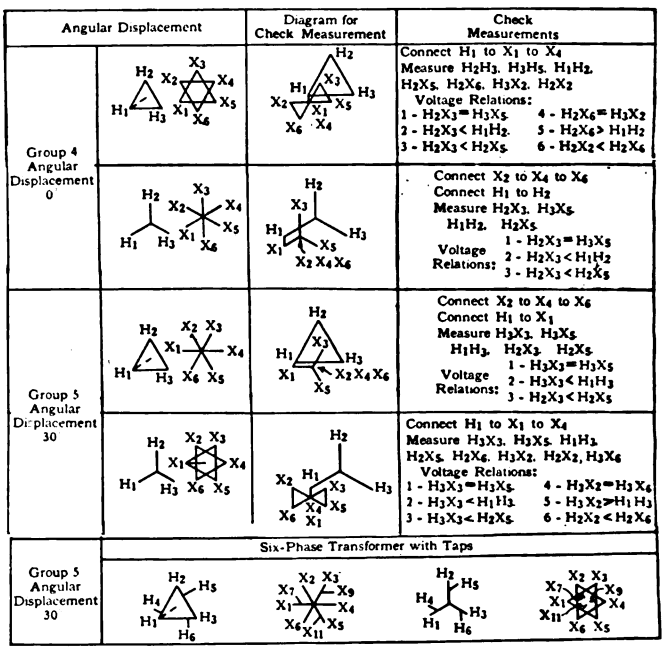


FIG. 129—TRANSFORMER LEAD MARKINGS AND VOLTAGE VECTOR DIAGRAMS FOR SIX-PHASE TRANSFORMER CONNECTIONS

time order of $X_1$, $X_2$, $X_3$ on the low-voltage side. The angular displacement between the high-voltage and low-voltage windings is the angle in each of the voltage vector diagrams, Fig. 128, between the lines passing from the neutral point through $H_1$ and $X_1$, respectively.

Transformers having leads marked in accordance with the above rules may be operated in parallel by connecting similarly marked leads together, provided their angular displacements are the same and provided, also, their ratios, voltages, resistances and reactances are such as to permit parallel operation.

Three-phase to six-phase transformers have the same lead markings on the three-phase side as three-phase transformers. The leads which connect to the full phase windings on the six-phase side are marked $X_1$, $X_2$, $X_3$, $X_4$, $X_5$, $X_6$. The markings are so applied

[1]Described in the JOURNAL for August 1928, p. 410

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that if the phase sequence of voltage on the three-phase side is in the time order $H_1$, $H_2$, $H_3$, it is in the time order of $X_1$, $X_2$, $X_3$, $X_4$, $X_5$, $X_6$ on the six-phase side. The angular displacement between the high-voltage and low-voltage windings is the angle in each of the vector diagrams Fig. 129, between the lines passing from the

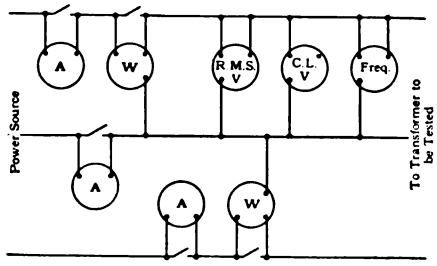


FIG 130—METER CONNECTIONS FOR MEASURING ALTERNATING-CURRENT POWER BY THE TWO-WATTMETER METHOD

neutral point through $H_1$, $X_1$, respectively. A three-phase to six-phase transformer is simply a three-phase transformer in which the secondary windings are so arranged that six-phase voltage can be obtained.

The Standards of the *A.I.E.E.*, No. 13, August, 1925, give three angular displacement groups for three-phase transformers and two angular displacement groups for three-phase to six-phase transformers. Groups 1, 2 and 3, show angular displacement of 0, 180 and 30 degrees, respectively. Groups 4 and 5 show angular displacement of 0 and 30 degrees, respectively. Groups 1 and 3 are commonly used for three-phase transformers and groups 4 and 5 for three-phase to six-phase transformers.

First determine the polarity of each phase in the same manner as described for single-phase transformers. Then connect the transformers in accordance with the three-phase connections. Assuming the three-phase connections to be delta-delta, apply a balanced three-phase voltage of low value to leads $H_1$, $H_2$, $H_3$. Measure the voltages $H_2$ to $X_2$, $H_3$ to $X_3$, $H_1$ to $H_2$, $H_2$ to $X_3$. If the transformer has standard polarity, $H_2$ to $X_2$ is equal to $H_3$ to $X_3$, $H_2$ to $X_2$ is less than $H_1$ to $H_2$, and $H_2$ to $X_2$ is less than $H_2$ to $X_3$. For three-phase Y-Y, delta-Y, or Y-delta connected transformers, the test procedure is carried on in a manner, similar to that described above. The connections, voltage measurements and voltage relations for these are also shown in Fig. 128. The polarity test for three-phase to six-phase transformers is conducted in a similar manner. The connections, voltage measurements and the voltage relations are shown in Fig. 129.

### PARALLEL WINDING TEST

The parallel winding test of a three-phase transformer is made by testing each phase separately. The procedure is the same as that described for single-phase units[1].

### MEASUREMENTS FOR RESISTANCE

In general, all leads from the windings of a three-phase transformer are brought to the terminal boards separately. The test is made by connecting the windings in delta, leaving one point open, and measuring the resistance of the three-phase windings in series. If the high-voltage or low-voltage windings are connected permanently in Y or in delta, the resistance between leads $H_1$-$H_2$, $H_2$-$H_3$, $H_3$-$H_1$ and so on must be measured. The measurements must be so recorded that a clear understanding may be had of the method employed.

### CORE LOSS AND EXCITING CURRENT

The instructions for measuring core loss of single-phase transformers[2], inclusive, are applicable, in general, to three-phase core loss measurements. In addition to these, the following instructions are given for three-phase measurements.

In a three-phase three-wire circuit, two wattmeters are generally employed. The algebraic sum of the two wattmeter readings gives the total watts. Figs. 130 and 131 represent the connections of the necessary meters for making the test. When it is found necessary to use voltage transformers, but no current transformers, do not connect the potential and current windings of the wattmeters together with a "static wire" as is sometimes done in single-phase measurements. Such connections will short circuit the high voltage directly through the wattmeters. The connections to the potential coils of the wattmeters, in Fig. 130, must always be made as shown, i.e., the potential terminal marked $\pm$ must be connected to the line in which the current coil of the wattmeter is connected. In both figures, the wattmeter connections shown are based on the assumption of a power-factor greater than 0.5. If the power-factor is below this value, one of the wattmeters may read backwards. In such case, the leads to the current coil of the affected meter should be interchanged, the source of power being disconnected meanwhile, and notation made that the wattmeter reading will be a negative quantity.

There are several test methods for determining the sign of the respective wattmeter readings, when the

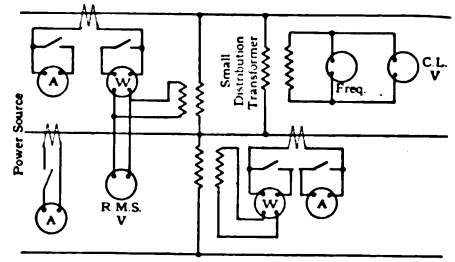


FIG. 131—METER CONNECTIONS FOR MEASURING ALTERNATING CURRENT POWER BY THE TWO-WATTMETER METHOD WHEN TRANSFORMERS ARE REQUIRED

same is not apparent from the wiring connections. The higher reading meter always is positive. The lower reading meter may be either positive or negative, depending upon the power-factor. A convenient test method for determining the sign of the lower reading

[2]Described in the JOURNAL for Sept. 1928, p. 457.

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meter is to disconnect the potential lead that connects to the phase in which no wattmeter current coil is connected, and connect it to the phase in which the other wattmeter current coil is connected. The direction in which the meter then reads is indicative of the sign for the former connection. Another test method is to open the phase to which the wattmeter in question is not connected. This leaves a single-phase circuit on the wattmeter. If the meter reads forward, the sign is positive for the three-phase connection; if it reads backward, the sign is negative.

In beginning the test be sure that the transformer windings are connected at the terminal board in accordance with the voltage value to be employed. Make the connections to a three-phase source of power of the proper frequency and apply a low value of voltage to the transformer being tested. Three-phase voltage readings on the secondaries of the voltage transformers should be taken to insure that the $V$ connection is properly made. The three-phase voltages should be practically equal. The value of the exciting current should be noted and if it is commensurate with the voltage applied, increase the voltage to normal gradually, taking frequent observations of the current value while so doing. When the voltage has been adjusted to normal, as indicated by the core-loss voltmeter, note and record the r.m.s. voltmeter reading after which the core-loss voltmeter and the frequency meter can be disconnected from the circuit. Read and record the current per phase and then close the wattmeter potential circuits and take the wattmeter readings.

If a step-down transformer is used in connection with the core-loss voltmeter, it should be disconnected from the circuit when finished with the core-loss voltmeter. Correction for the loss in the wattmeter potential circuits and the voltage transformers should be made as previously described. The volt-amperes excitation (apparent watts core loss) is computed from the average current of the three phases times the line voltage times 1.73.

### COPPER LOSS AND IMPEDANCE

The total $I^2R$ loss of a three-phase transformer may be calculated by using the following formula. Let $R_1$ and $R_2$ be respective resistances between two line terminals of the respective high-voltage and the low-voltage windings, and $I_1$ and $I_2$ be the respective line currents in amperes. The total $I^2R$ loss of the three phases will then be equal to 1.5 $(I_1^2R_1 + I_2^2R_2)$ watts. Since the resistances of the three-phases usually are measured, connected in series, the general rule is to calculate the winding currents and then compute the $I^2R$ losses in the same manner as for single-phase transformers.

The copper loss and impedance tests by wattmeter of a three-phase transformer may be made with either single-phase or three-phase power. The general practice is to use three-phase power. The general instructions given for single-phase copper-loss tests are applicable in a way to the copper-loss and impedance tests on three-phase transformers. Otherwise the procedure is similar to that described for the three-phase core loss tests. Connect the transformer, as shown in Fig. 132, or its equivalent, connect the instruments in the circuit, as shown in Figs. 130 or 131, omitting the core-loss voltmeter. Adjust the applied voltage to give equal values of rated current in each line. If balanced current values cannot be obtained, adjust the current in the three lines so that the average value will be equal to the rated current value. Take wattmeter readings in the same manner as directed for the core-loss tests. Measure and record the impedance voltage of each phase. The average value of these voltages is taken as the impedance voltage of the transformer.

If the test is made with single-phase power, the high-voltage and the low-voltage windings are connected in delta. One of the deltas is opened and sufficient single-phase voltage is applied to cause normal rated current to flow. The procedure is then the same as for

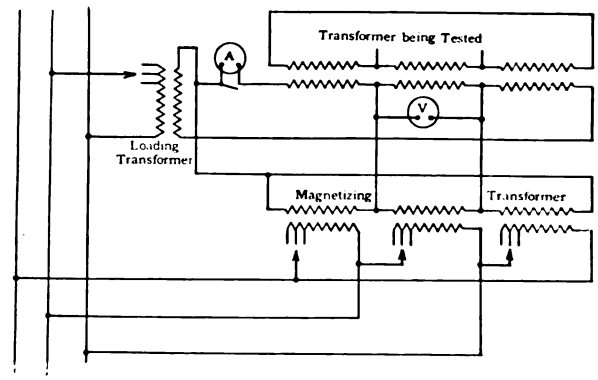


FIG. 132—CONNECTIONS FOR COPPER LOSS TEST

a single-phase copper loss and impedance test. In this test, it is obvious that the measured impedance voltage is the sum of the impedance voltages of the three phases. To put this in terms of the three-phase impedance, the normal three-phase connections of the windings to which the power is applied must be taken into account. If the windings are designed for delta connections:—

$$\text{Percent impedance voltage} = \frac{\text{Measured impedance voltage} \times 100}{3 \times \text{rated line voltage}}$$

If the windings are designed for star connections:—

$$\text{Percent impedance voltage} = \frac{\text{Measured impedance voltage} \times 1.732 \times 100}{3 \times \text{rated line voltage}}$$

### TEMPERATURE TESTS OF THREE-PHASE TRANSFORMERS

Temperature tests of three-phase transformers are similar to the temperature tests of corresponding types of single-phase transformers. In the case of three-phase transformers, the usual practice is to connect the high-voltage and low-voltage windings in delta and, with one of the deltas opened, circulate the load current with single-phase power. Three-phase magnetizing voltage is applied to either the high-voltage or the low-voltage winding, depending upon which is most

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convenient for the particular case in hand. The usual method of connection for the test is shown in Fig. 132. Two similar three-phase transformers may be tested by the loading-back method, as shown in Fig. 133. In this method, both the copper loss and core losses are supplied by three-phase power, consequently three auxiliary single-phase transformers are required for circulating the load currents. Owing to the additional equipment required and that the single-unit method suffices for all practical purposes, the latter method seldom is employed.

When setting up and preparing for the test, the general instructions given for corresponding types of single-phase transformers should be followed insofar as they are practicable. The resistance to be used in computing the temperature rises should be measured in the same manner as described for the resistance test[1]. Arrange the delta connections in such a manner that they can be quickly opened for the hot resistance measurements. If the transformer is of the air blast type, place as many thermometers on each phase as are ordinarily used on a single-phase transformer. If the transformer is of the oil-insulated self-cooled, oil-insulated water-cooled or oil-insulated forced-cooled type, the temperature of the top oil over each phase should be taken when possible. In other respects, the test is conducted similar to those described for the corresponding types of single-phase transformers.

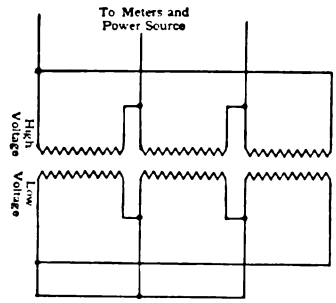


FIG. 133—CONNECTIONS FOR TEMPERATURE TEST ON A THREE-PHASE TRANSFORMER

### INSULATION TESTS OF THREE-PHASE POWER TRANSFORMERS

The insulation tests of three-phase transformers are practically the same as those for single-phase transformers. The instructions given for single-phase transformers, therefore, are applicable, in a general way, for three-phase transformers. The usual practice in making the test from the high-voltage windings to the low-voltage windings and the core is to test the three phases simultaneously. The test from the low-voltage windings to the core is made in a similar manner. As a general rule, the insulation resistance measurements are made with three phases connected together (a multiple condition), hence the measured value may be only one-third of the real value of the individual phases. The over-potential tests are conducted in the same manner as for single-phase units, except that three-phase voltage is employed. If the transformer being tested is designed for star connection on the high-voltage side, it must be so connected for the over-potential test. When a three-phase source of voltage is not available and the test is to be made with single-phase power, the dielectric tests of the high-voltage winding to the low-voltage winding and core must be made on each phase separately. At the same time, connect all windings of the other phases to the core and case.

### TRANSFORMER EFFICIENCY AND REGULATION

The efficiency of a transformer is the ratio of the kv-a output to the kv-a output plus the total losses at 75 degrees C. The efficiency is usually expressed in terms of unity power-factor. A tabulation of efficiency calculations for a typical transformer is given in Table LIX. The efficiency at full-load, unity power-factor, for instance, is calculated as follows:—

$$Efficiency = \frac{1000}{1000 + 11.7} = 0.9884 \text{ or } 98.84 \text{ percent.}$$

TABLE LIX—LOSSES AND CORRESPONDING EFFICIENCIES FOR A SINGLE PHASE 1000 KV-A, 22 000-2300 VOLT, 60 CYCLE, OIWC TRANSFORMER

| Load | Core Loss in Kw | Copper Loss in Kw | Total Losses in Kw | Percent in Kw |
|---|---|---|---|---|
| 1 | 4 2 | 7 5 | 11 7 | 98 84 |
| ¾ | 4 2 | 4 220 | 8 42 | 98 88 |
| ½ | 4 2 | 1 875 | 6 07 | 98 78 |
| ¼ | 4 2 | 0 469 | 4 67 | 98 13 |

The copper loss as measured by wattmeter at a temperature of $t$ degrees C. is corrected by a temperature of 75 degrees C., as follows:—

Let $P_t$ = Watts copper loss as measured by wattmeter at temperature of $t$ degree C.
$P_{75}$ = Watts copper loss corrected to 75 degrees C.
$I^2R$ = $I^2R$ corrected to $t$ degrees C. as observed in copper-loss test.
$I^2R_{75}$ = $I^2R_t$ corrected to 75 degrees C.

Then,—

$$P_{75} = (P_t - I^2R_t) \times \left(\frac{234.5 + t}{234.5 + 75}\right) + I^2R_{75}$$

### TESTS AND COMPUTATION OF REGULATION

The regulation of a constant-potential transformer is the difference between the no-load and rated-load values of the secondary terminal voltage, expressed in percent of the rated-load secondary voltage, with the primary impressed terminal voltage adjusted to such a value that the transformer delivers rated kv-a output at a specified power-factor and at rated secondary voltage.

The regulation for any specified load and power-factor may be computed from the measured copper-loss watts and impedance volts, as follows:—

Let,—$P$ = Watts copper loss as measured in short-circuit test, and corrected to 75 degrees C.
$P_{75}$ = Watts copper loss as measured in short-circuit test, and corrected to 75 degrees C.
$E_z$ = Impedance volts as measured in the short-circuit test (impedance drop).
$IX$ = Reactance drop in volts.
$I$ = Rated primary current.
$E$ = Rated primary voltage.
$q_r$ = Percent drop in phase with current, i.e., resistance drop.
$q_x$ = Percent drop in quadrature with current, i.e., reactance drop.
$m$ = Power-factor of inductive load = cosine of the angle between current and voltage.
$n$ = Reactive-factor of inductive load = sine of the angle between current and voltage.

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Then, for unity power-factor we have:—

$$\text{Percent regulation} = q_r + q_x + \frac{s^2}{200}$$

$$q_r = 100\,\frac{P}{EI}$$

$$q_x = 100\,\frac{IX}{E}$$

$$IX = \sqrt{E_z^2 - \frac{P^2}{I}}$$

For inductive loads of power-factor $m$ and reactive-factor $n$.

$$\text{Percent regulation} = mq_r + nq_x + \frac{(mq_x - nq_r)^2}{200}$$

For example, consider the transformer whose data is given in Table LIX. The impedance voltage is 1034 volts.

$P_{75}$ = 7.5 kw = 7500 watts.
$E_z$ = 1034 = 4.7 percent.
$E$ = 22 000 volts.
$I$ = 1000 kv-a ÷ 22 000 = 45.5 amperes.

$$IX = \sqrt{1034^2 - \left(\frac{7500}{45.4}\right)^2} = 1022 \text{ volts.}$$

$$q_r = 100\,\frac{7500}{22\,000 \times 45.4} = 0.75 \text{ percent.}$$

$$q_x = 100\,\frac{1022}{22\,000} = 4.65 \text{ percent.}$$

Then for unity power-factor,—

$$\text{Percent regulation} = 0.75 + \frac{4.65^2}{200} = 0.85 \text{ percent.}$$

For inductive load of 80 percent power-factor.

$$\text{Percent regulation} = (0.8 \times 0.75) + (9.6 \times 4.65) + \frac{(0.8 \times 4.65) - (0.6 \times 0.75)^2}{200} = 3.44 \text{ percent.}$$

A simple method for determining $q_x$ is to express $P_{75}$ in percent of the rated kv-a, which equals $q_r$ and the impedance volts in percent which equals $q_z$.
Then,

$$q_x = \sqrt{q_z^2 - q_r^2}$$

In computing the regulation of a bank of two transformers connected for Scott three-phase to two-phase transformation, the regulation of the main phase is computed as for a regular single-phase transformer. The regulation of the teaser phase is computed from the sum of the percent $IR$ and the percent $IX$ drops, as determined from tests 1 and 2,[2] expressed in percent of 86.7 percent of the primary line voltage.

### TEMPERATURE CORRECTIONS FOR COOLING OF TRANSFORMER WINDINGS AFTER SHUT DOWN

Since a drop in temperature occurs in a winding between the instant of shut-down and the time of measuring hot resistance, a correction shall be applied to the temperature determined from this measurement so as to obtain, as nearly as practicable, the temperature at the instant of the shut down. This correction can be determined approximately by plotting a time temperature curve, with temperature as ordinates and time as abscissae and extrapolating back to the instant of shut down. In certain cases, however, other correction factors can be applied. In the case of oil immersed transformers the following method recommended by the A.I.E.E., rules No. 13, August, 1925, on account of the greater accuracy obtainable under ordinary testing conditions.

"When the copper loss, as determined by wattmeter measurements does not exceed 30 watts per pound, the correction in degrees C. may be taken as the product of the watts per pound of copper for each winding multiplied by a factor that depends upon the time elapsed between the instant of shut down and the time the resistance measurement is taken, as given in Table LX. For intermediate times, the values of the factor may be obtained by interpolation."

In order to further simplify the operation of correcting the observed temperature to the instant of shut down, the chart, shown in Fig. 134, can be used. The correction in degrees C., obtained by the use of this chart, is in practical agreement with the rules given in the preceding paragraph.

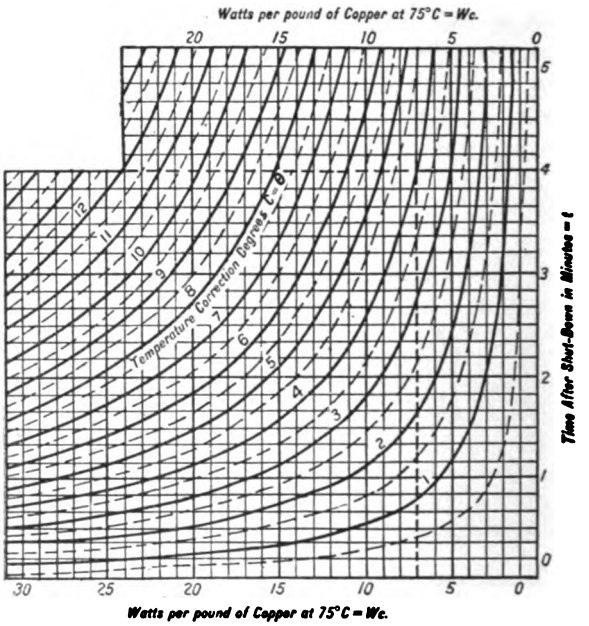


FIG. 134—TEMPERATURE CORRECTION FOR OIL-IMMERSED TRANSFORMERS

Calculated from the formula*

$\theta = 1.95\ W_c^{0.7}\ (1 - \epsilon^{-n})$

where $n = 0.106\ W_c^{0.3} t$

The A.I.E.E. rules No. 13, August, 1925, further gives:—"When the copper loss, measured by wattmeter does not exceed 7 watts per pound, an arbitrary correction of one degree per minute may be used, provided the elapsed time between the instant of shut down and the measurement of the hot resistance does not exceed 4 minutes." This rule applies principally to distribution transformers.

"Air-blast transformers: An arbitrary correction of one degree per minute may be used provided the time elapsed between the instant of shut down and the measurement of hot resistance does not exceed four minutes."

*See the *Proceedings of the A.I.E.E.* for April 1927.

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# The Use of Steel in Switchboard Design

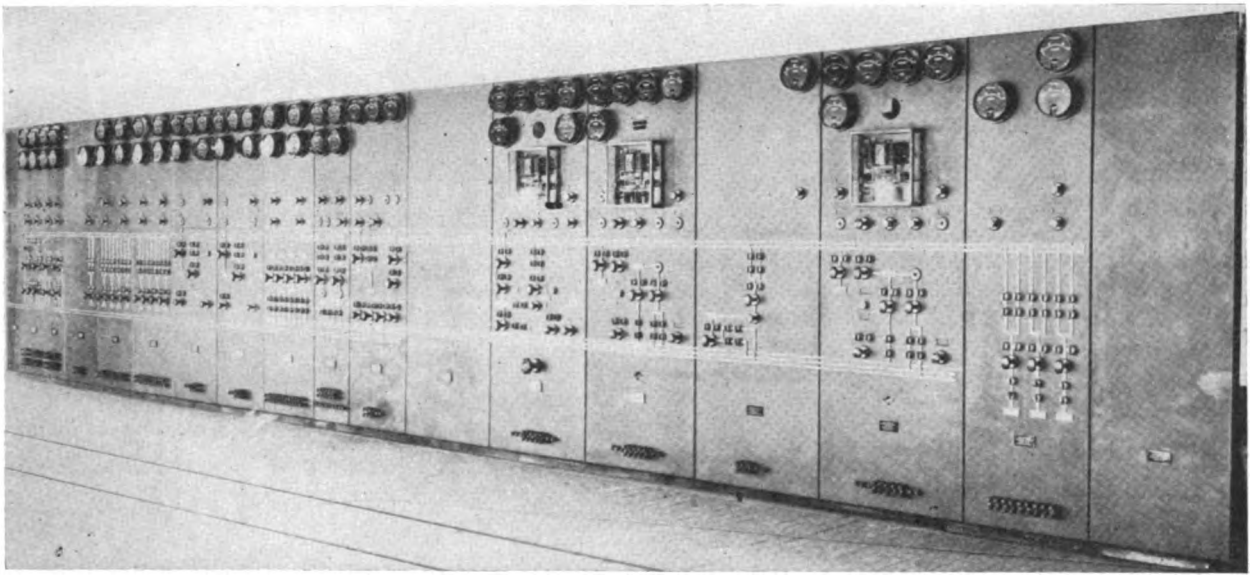
T. A. KENNY
Engineering Dept.,
West Penn Power Co., Pittsburgh, Pa.

THE advent of electric power required the development of some means for controlling it. The voltage and capacity of the early electrical installations were low, and only simple means were required to control the electrical energy.

The early switchboards were constructed of matched boards fitted together. Switches, instruments, breakers and other pieces of apparatus were mounted on individual bases, usually made of marble. The different devices were then grouped symmetrically on the front of the wooden panel, and wires were brought through the board at convenient points and were run along the front of the panel.

As the electrical art progressed, it was soon recognized that wooden panels introduced a fire hazard which was a constant menace to the operation of the station. Marble was then introduced as a material for switchboard panels, because of its good dielectric properties, and its attractive appearance. Control devices were mounted directly on the panel, instead of on individual bases, and all wiring was on the rear of the board. It was found, however, that marble panels were easily marred with scratches and oil stains, and a great deal of effort was required to maintain their attractive appearance.

In order to eliminate this disadvantage, slate was used in spite of its inferior and less uniform dielectric properties. Because of its limitations as a dielectric material, the use of slate was at first restricted to the lower voltage installations, but in spite of this, its use increased due to its excellent mechanical strength. The generation and consumption of electrical energy at ever increasing voltages and higher current capacities, made it necessary to develop remote control, not only as a safeguard to the operator, but also because the physical size of the control devices made it impossible to mount them directly on the panel. Instrument transformers were also developed to operate meters and other instruments, so that only moderate voltages were used on switchboard panels; hence, the dielectric strength of slate no longer limited its application. A black enamel finish for slate proved unsatisfactory because of its tendency to chip, so a flat black pyroxyline finish was developed. High grade, oil-polished, natural black slate was also used.



AN 18 UNIT, STEEL-PANEL SWITCHBOARD OF MODERN DESIGN

With a mimic bus to enable the operator to diagnose switching operations more readily. The indicating instruments have black dials with white markings and pointers, as these have been found to be less subject to glare from artificial lighting than instruments with white dials and black markings.

At first, instruments were bulky and cumbersome and required large switchboard panels. However, considerable progress had been made in producing much smaller and more accurate instruments, and this permitted a material reduction in the height and width of switchboard panels, which made possible more concentrated control.

As the use of slate increased, it became apparent that the breakage of switchboard panels in transit or

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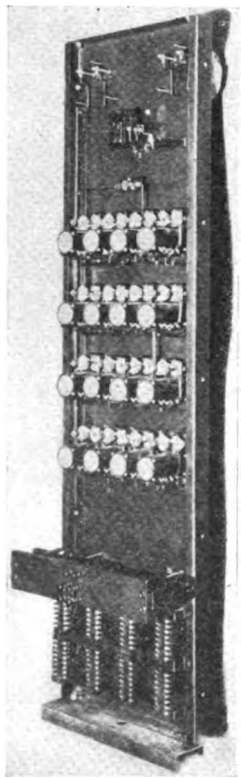
in handling was serious. Some engineers advocated the use of asbestos lumber for switchboards, believing it less subject to breakage than slate or marble. The appearance of this material was easily marred from careless handling in manufacture or installation, and once damaged, it was difficult to restore the finish. Also this material was subject to warping.

Since all of the previously mentioned materials had proved more or less unsatisfactory for switchboard use, engineers have recently turned to steel as a solution to the problem. The growth of the automobile and steel furniture industries had brought about the development of attractive and durable finishes which were easily applied, and well suited to switchboard requirements. The early steel panels consisted of flat sheets of heavy gauge steel of the same size as the slate panels,

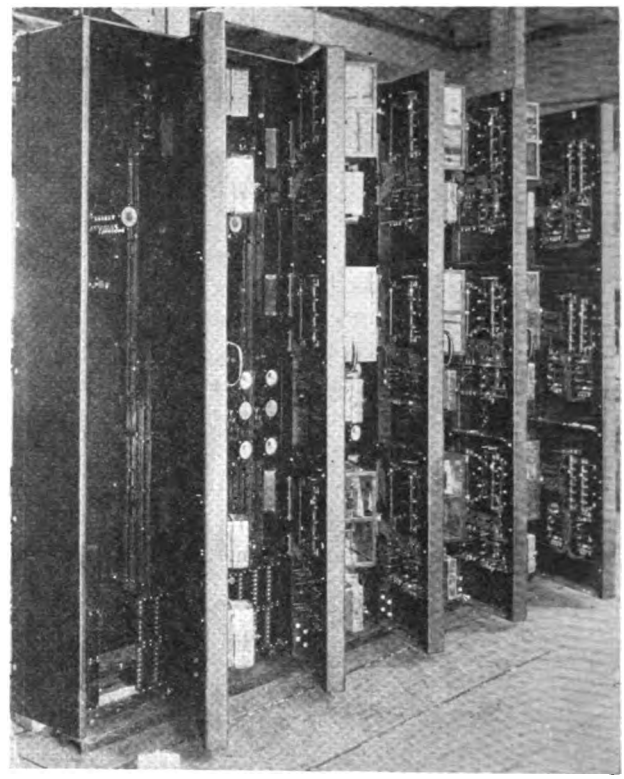


THE REAR OF A SINGLE-UNIT PANEL

This shows the method of wiring and bolting adjacent panels together. Suitable insulating bushings are slipped over the meter studs which project through the panel and thus insulate them from the steel. There are no exposed electrical devices or wiring on the front of these modern boards.

mounted on frames, as all previous panels had been mounted. In order to secure proper alignment when mounting several panels together, it was found necessary to machine the edges of the panels, and this entailed considerable expense. The unbreakable feature of the early steel panel was its real advantage over slate and marble panels.

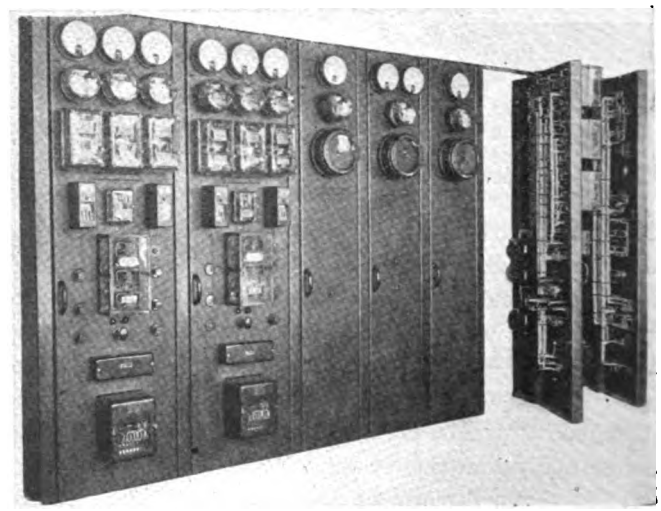
After a long period of experimentation, a steel panel was produced which eliminated all of the previous difficulties. These panels are made of 1/8 inch stretcher leveled steel, the sides being bent into a channel section about three inches deep. The top and bottom edges of the panel are bent into a three inch angle section, and the corners are welded and ground smooth. All front edges are rounded to a three-eighths inch radius. After being welded and ground, the panel is sand-blasted, and the first coat of finish applied. When the panel has been completely drilled, it is finished in soft black, or any other desired color. The control devices and meters are then mounted and the



A COMPLICATED BOARD WITH SWINGING DOORS

Which carry the instruments and relays. The other side of the cabinet is stationary and also carries additional electrical control equipment. Flexible wiring permits the doors to swing freely when opened. The bent sides of the steel door provide rigidity when mounting heavy equipment.

wiring completed. All vertical wiring is run in the side channels and is concealed by cover plates which can readily be detached. Only the horizontal wires are



ANOTHER SWINGING PANEL STEEL SWITCHBOARD

With some of the panels swung open.

visible, and this produces a much neater job without sacrificing the accessibility of the wiring.

The panels are self-supporting, requiring no external framework. This makes possible great savings of time, labor and material in installing them. The com-

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pleted panels are light, weighing about 25 percent as much as similar slate panels, and consequently transportation charges are reduced. Breakage of the panel itself is eliminated, and scratches may easily be removed by refinishing the spot with some of the original quick-drying lacquer. Because of their lightness and rigidity, steel panels are frequently mounted on hinges, close to the wall. The wiring is readily inspected by swinging the panels open, and a great saving in floor space is thus effected. The panels can readily be reinforced to carry as heavy equipment as is now commonly mounted on any type of switchboard. Studs can readily be insulated from the panel by passing them through insulating bushings, or by drilling holes which give ample clearance. In appearance the modern steel switchboard panel represents a marked advance over other types. Absence of mounting bolts and horizontal sectional breaks, is a large factor in this improved appearance.

The previous paragraphs have pointed out the following advantages of modern steel panels over other types of panels:—

1—Lower first cost.
2—Lower installation cost.
3—External framework eliminated.
4—Less floor space required.
5—Lighter, more rigid, and unbreakable.
6—Attractive appearance.
7—Appearance easily maintained.

Since each of the above features represents a distinct advantage, it seems safe to predict that the steel switchboard panel will enjoy rapidly increasing popularity.

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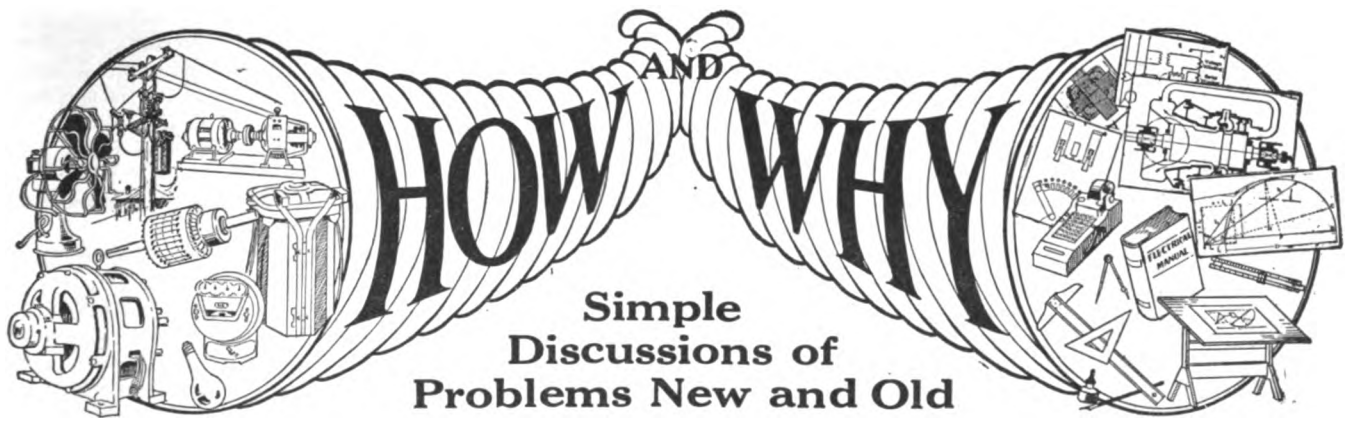


# Ammeter Shunts for Large Capacity Circuits

PAUL MacGAHAN

THE measurement of large capacity direct-current circuits involves problems of overcoming difficulties and sources of error not present in the case of lower capacity units of power. The measurement of the amperes by means of millivoltmeters operating from ammeter shunts up to about 5000 amperes is far simpler than the measurement of circuits carrying 10 000, 20 000 or 30 000 amperes.

In the first place, the amount of heat generated in the shunt is proportional to the amperes, as the millivolts required by the milli-voltmeter is generally a fixed quantity, such as 50 milli-volts, for all capacities. The heat generated in the shunt is dissipated by convection of air currents, radiant heat and by conduction from the terminals into the connecting bus bars or cables. As shunts become larger, their radiating surface and convection effects do not increase in direct proportion to their cross section and it is therefore necessary that the sizes of a line of otherwise similar shunts increase more rapidly than the rated capacity in amperes. Thus, a 10 000 ampere shunt will be considerably more than twice as large and twice as expensive as a 5000 ampere shunt.

Another problem is the difficulty of calibrating these large shunts due to the variations in millivolt drop arising from unequal distribution of current to the terminal blocks. This distribution of current depends upon contact resistance of the surfaces of the various bus bars or connecting cable lugs where they are connected to the terminals. It is very difficult to duplicate the actual conditions which will exist in service when calibrating and vice-versa, it is very difficult to insure that the distribution, and therefore the millivolt drop occurring in service, will be the same as that which existed when calibrating.

A simple and satisfactory solution of these problems recommended and placed into effect on many installations by the meter engineers of one instrument manufacturer has been to use several smaller capacity shunts in multiple for measuring heavy blocks of current. For example, instead of installing a 20 000 ampere shunt, it is far more satisfactory to install four 5000 ampere shunts in parallel. With this arrangement, it is not necessary for the currents to divide equally between the four shunts. It is desirable only from the point of view of heating effects to so arrange the bus bars that each shunt will carry approximately its own share of the load.

However, it is necessary to bring to the millivoltmeter terminals separate millivoltmeter leads from each shunt. The millivolt drops at terminals of the instrument will then be the average of the drops across the individual shunts and according to both calculations and actual tests, no appreciable error is introduced by this method.

In line with regular practice, each shunt is calibrated separately for a fixed millivolt drop of 50 at its full-load rating and the millivoltmeter is calibrated separately to give full scale readings when 50 millivolts is applied to the outer or shunt end of the millivoltmeter leads. In the case of multiple shunts with separate leads, the millivoltmeter must be calibrated with all these leads in parallel.

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# Motor Field Rheostat Design

REUBEN LEE

THE speed of a direct-current shunt or compound motor may be regulated above normal speed within certain limits by means of a rheostat in the shunt field. The lower limit of this type of speed control is the full field speed. To obtain speeds below this, armature control is necessary. The upper limit of speed is determined by the armature current which will overheat the motor. Mechanical limitations imposed an additional upper maximum speed. Between these limits it is possible to regulate the speed very closely by means of an adjustable resistance or rheostat in series with the shunt field. The degree of exactness, which depends upon the requirements of the driven load, is obtained by dividing the rheostat into a sufficient number of steps.

As the operator moves the rheostat arm from one step to the next, he rightly expects about the same increase or decrease in speed with each step. Consequently, it is the usual practice to provide approximately equal speed increments per step throughout the rheostat range.

Proportioning the rheostat, then, consists of two main problems:—1—Including sufficient ohms resistance to obtain

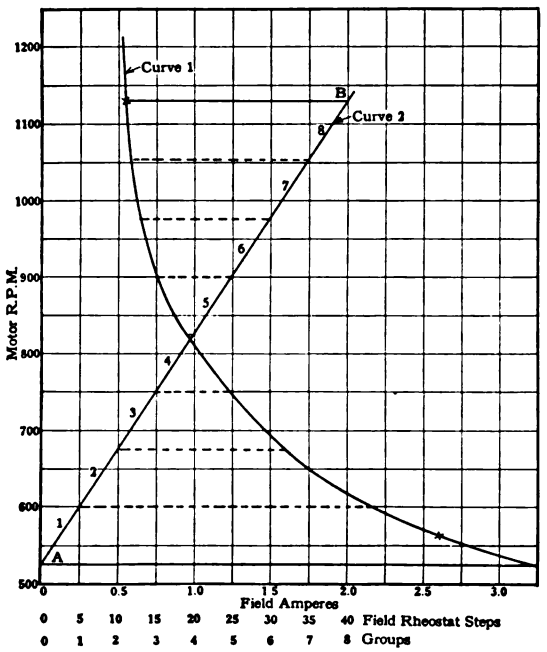


FIG. 1—SHUNT-MOTOR SPEED CHARACTERISTIC USED IN RHEOSTAT DESIGN

the maximum permissible motor speed. 2—Distributing this resistance so as to produce equal speed increments per step.

The motor characteristics enter into the problem to a large extent. The basic data from which a field rheostat is calculated are the shunt field amperes and corresponding speeds, recorded during an actual test of the motor under full-load conditions. Enough points should be taken to cover the entire operating range.

Such data taken from a typical 75 hp, 230 volts, shunt-wound motor, having a speed range of 565 to 1130 r.p.m., is plotted in curve 1, Fig. 1. This curve is a hyperbola, distorted by the combined effects of armature reaction, series field, and field pole saturation. The field circuit resistance at the temperature corresponding to maximum field current is also usually supplied, although it may be found by dividing the line voltage by this current. From the data in curve 1, this hot field resistance is $230/2.65 = 90$ ohms.

The field rheostat must provide enough resistance to obtain maximum speed under all conditions, even when the motor has been allowed to cool, and the field resistance is reduced to the cold field value. If it cannot be obtained readily by test, this value may generally be taken as 80 percent of the hot field resistance, or 72 ohms in this case. Curve 1 is extended to include the cold field maximum current, which is $230/72 = 3.2$ amperes.

After the field has been heated to some extent, the speed attainable with all the field rheostat in the circuit exceeds the maximum of 1130 r.p.m. Also, the no-load speed at this point is considerably higher than 1130 r.p.m. It is, therefore, necessary under either of these conditions to move the rheo-

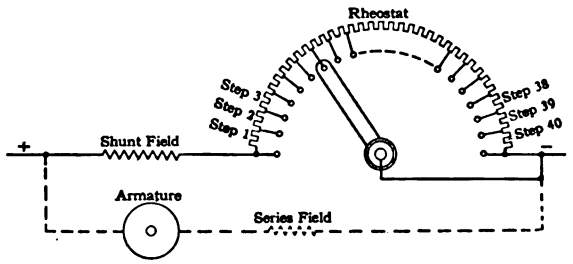


FIG. 2—SCHEMATIC DIAGRAM OF A RHEOSTAT CONTROLLED SHUNT MOTOR

stat arm back, that is, decrease the resistance, in order to keep the maximum speed within the permissible speed range of the motor. If this is more objectionable, from the operator's standpoint, than being unable to secure maximum speed at full load or with cold field, it can be overcome by short-circuiting one or more steps of the field rheostat. Usually, however, such an objection is not raised, and it is necessary only to keep within the mechanical speed limit.

Determining the number of steps to be used is the next step in the rheostat design. The primary factor entering here is the accuracy of speed required, although the voltage drop per step has an influence as will be seen later.

Assuming that forty steps provide sufficiently small speed increments, these steps are laid out as abscissae to any convenient scale and are numbered to correspond with the diagram of Fig. 2. Thus, when the rheostat arm is moved to step 40, the whole rheostat is in the field circuit, and the motor speed is 1130 r.p.m. at full load. Also, when the arm reaches step 0, none of the rheostat is in circuit, and the full-load speed is 513 r.p.m., with cold field. These relations fix the positions of points *B* and *A*, respectively, on Fig. 1, through which the straight line curve 2 can be drawn. Since equal portions of this line have equal vertical and equal horizontal projections, the rheostat steps represent equal increments of speed.

Although the field current changes with the different steps, the amount of variation on adjacent steps is not large. In fact, small groups of steps may be treated as having no variation in field current whatever, without departing materially from the provision of equal speed increments per step. In this way, the amount of calculation may be reduced considerably. By dealing with groups of five steps, the figuring is reduced to one-fifth of that required for separate calculation of each step.

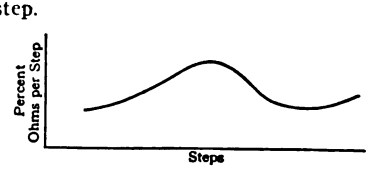


FIG. 3—TYPICAL RESISTANCE DISTRIBUTION IN A RHEOSTAT

If the straight line of curve 2 is divided into eight equal parts, that is, the number of groups of resistance steps selected, and from these divisions horizontal lines are projected to curve 1, the field amperes corresponding to equal speed increments can readily be found and tabulated for each group. Thus in increasing the speed from 600 to 675 r.p.m., for example, the field current must change from 2.18 to 1.60 amperes. In increasing the speed from 900 to 975 r.p.m. the field current must change from 0.75 to 0.65 am-

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peres, a much smaller decrement. The field rheostat must be so designed that the insertion of group 2 into the field circuit will lower the current from 2.17 to 1.6 amperes and the insertion of group 6 must lower the current from 0.75 to 0.65 amperes. Thus each group will vary the motor speed by 75 r.p.m. The results of these calculations are given in Table I.

The maximum amperes of column 2 are the current values just before the insertion of the group into the field circuit, the minimum values of column 3 being the current when the whole group is inserted. Thus, the minimum amperes for any group are the maximum amperes for the next group. The total field circuit ohms corresponding to these values of current form the next two columns, and are found by dividing the voltage, 230, by the current. The difference between them, or the ohms per group, form the sixth column.

TABLE I—RHEOSTAT DATA

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Initial | | Revised | | |
| | Amperes | | Ohms | | | | | | | |
| Group | Max. | Min. | Min. | Max. | Ohms. per Group | Ohms. per Step | Max. volts per Step | Ohms. per Step | Max. volts per Step | Amp. Capacity. |
| 1 | 3.2 | 2.18 | 72 | 105 | 33 | 6.6 | 21.1 | 5.6 | 18.0 | 2.96 |
| 2 | 2.18 | 1.60 | 105 | 144 | 39 | 7.8 | 17.0 | 7.8 | 17.0 | 2.13 |
| 3 | 1.60 | 1.25 | 144 | 184 | 40 | 8.0 | 12.8 | 8.0 | 12.8 | 1.57 |
| 4 | 1.25 | 0.95 | 184 | 242 | 58 | 11.6 | 14.5 | 11.6 | 14.5 | 1.21 |
| 5 | 0.95 | 0.75 | 242 | 307 | 65 | 13.0 | 12.4 | 14.0 | 13.3 | 0.92 |
| 6 | 0.75 | 0.65 | 307 | 354 | 47 | 9.4 | 7.1 | 9.4 | 7.1 | 0.73 |
| 7 | 0.65 | 0.60 | 354 | 384 | 30 | 6.0 | 3.9 | 6.0 | 3.9 | 0.64 |
| 8 | 0.60 | 0.55 | 384 | 419 | 35 | 7.0 | 4.2 | 7.0 | 4.2 | 0.59 |
| | | | | | 347=Total ohms in rheostat | | | | | |

To obtain the ohms per step divide by five. Multiplying the latter column by the corresponding values of maximum current gives the volts per step. These volts must be kept below a certain safe value, which depends upon the rheostat physical proportions.

Assuming that the resistance units to be used have a maximum safe voltage of 18 volts per step, it will be noted that this value is exceeded in the first group only. This condition is remedied by distributing some of the ohms of group 1 to other groups where they will have the least effect upon the equal speed distribution per step.

With the volts across the first step limited to 18, the ohms per step in the first group are reduced from 6.6 to 5.6. The difference can easily be transferred to group 5, which has the greatest number of ohms per step, without materially changing the values of either ohms or volts in this group. If the initial values of ohms per step had resulted in such high voltages per step as to make objectionably unequal speed divisions necessary, another design of rheostat would have to be used, having either more steps or higher permissible volts per step.

Tubes, plates, or other units comprising the resistor must be able to carry continuously the current values given in the last column. These values are obtained by inserting the first step of resistance in the circuit for each group, and therefore are smaller than the maximum amperes per group. The resistor units are generally made in standard sizes, which do not differ by smaller variations than the amperes per group.

It is of interest to note the way in which the ohms per step vary over the rheostat range, increasing from the first to the fifth group, then decreasing until the last group, where another increase occurs. This somewhat puzzling behavior is the result of two opposing factors. The first is the effect of the shape of curve 1. In the first few steps, the current variation per step is much greater than in the last few. This, therefore, points to a decrease in the ohms per step when proceeding from step 1 to step 40.

The opposing tendency is produced by the fact that a larger number of ohms is required for a given current variation with small currents than with larger currents. In other words, 10 ohms form a greater percentage of 100 ohms than of 500 ohms.

The ohms per step increase or decrease, depending upon which of these two effects predominates. In groups 1, 2, 3, 4, 5 and 8 the second is more pronounced, while in groups 6 and 7 the first is the greater effect. Sometimes only one of these effects is evident throughout the entire range.

A rheostat designed in this manner affords close speed regulation that approximates the uniformity of curve 2. At the same time, laborious calculations are reduced to a minimum.

In cases where equal speed divisions per step are not essential, still further approximations are made. The ohms per step as found above are plotted against the corresponding steps, as shown in Fig. 3, the ohms being expressed as a percentage of the total ohms in the rheostat. Curves of this kind for many different motors are plotted, and an average or mean curve for the group is chosen. The latter curve is then used as a guide in laying out the rheostat for any motor in the group. This method is exceedingly simple, involving practically no calculations after the mean curve is once chosen. It is especially useful when large numbers of rheostats are applied to a standardized line of motors, and equal speed steps are not of prime importance.

# The JOURNAL QUESTION BOX

Our subscribers are invited to use this department as a means of securing authentic information on electrical and mechanical subjects. Questions concerning general engineering theory or practice and questions regarding apparatus or materials desired for particular needs will be answered. Specific data regarding design or redesign of individual pieces of apparatus cannot be supplied through this department.

To receive prompt attention a self-addressed, stamped envelop should accompany each query. All data necessary for a complete understanding of the problem should be furnished. A personal reply is mailed to each questioner as soon as the necessary information is available; however, as each question is answered by an expert and checked by at least two others, a reasonable length of time should be allowed before expecting a reply.

2877—CURRENT IN UNDERGROUND CABLE SHEATH—We have four three-conductor 400 000 c.m. lead covered, oiled cambric cables, 600 feet long, carrying from 270 to 300 amperes at 2300 volts, laid in fibre ducts imbedded in concrete three feet under ground. I find there is considerable induction between the cables. When working in one of the manholes we experienced difficulty with the inductive current. We tried bonding the cables, but found the amperes so great that we were afraid the lead would melt. Will you kindly advise the best way of handling such cables when alive. We are expecting to pull in another parallel cable. How can we best overcome the induction in it from the other cables?

A. D. H. (BRITISH COLUMBIA)

The lead sheath of a single-conductor cable is a conductor in parallel with the copper current-carrying conductor. If such cables are used to carry alternating current, voltage will be induced in the sheath by the current flowing in the conductor. If the sheaths of a circuit are not bonded or grounded, there is no circuit in which current may flow, and the result is an external manifestation of voltage along the cable sheath. If one end of the line is grounded, this voltage will appear as a voltage above ground and between sheaths at the ungrounded end of the line, and to a lesser degree at intermediate points. If the ends of the lead sheaths are bonded together, the in-

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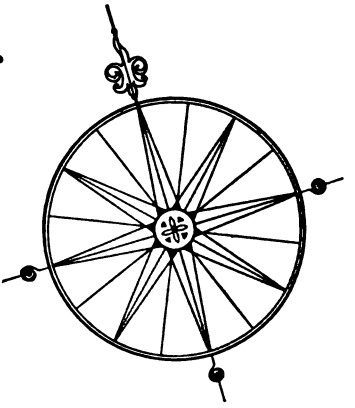
# 2 plants locate economies
## —with the same compass



### In Plant No. 1
### Repairs, replacements, and the reboring of cylinders eliminated

This western public utility operates a 5,000-h.p. cross-compound Corliss steam engine.

In 1917 and again in 1919 the cylinders had to be rebored at a total cost of $750. Repairs and replacements of piston rings and piston packing were high.

In 1921 a change was made to Gargoyle lubricants—Gargoyle Cylinder Oil 600 W for high pressure cylinders, and Gargoyle Cylinder Oil Rarus for low pressure cylinders.

A report on October 20, 1927, showed no cylinder reboring in 6 years and not a single repair or replacement of packing or piston rings.

(From the records of an Indiana power and light company)
Vacuum Oil Company File No. 102027

The money saved by this company is an item in itself.

But the greater saving is the combined cost of repairs, cost of the labor in making these repairs, and the loss of time while the engine was out of service.

Depreciation must also be taken into consideration for there is a limit to the number of times a steam cylinder can be rebored.

### In Plant No. 2
### 5 Turbines—10 Years —Gargoyle D.T.E. Oil Light —reliability of service

Ten years ago this Ohio power and light company selected Gargoyle D. T. E. Oil Light for the lubrication of steam turbines in its new plant.

Reasons for this decision were based upon the paramount necessity of taking no chances with reliability of operation, in view of the high load factor of the station.

Of the 125 stations in the United States producing one hundred million k.w. hours or over in 1926, this station had the highest percentage load factor—89.4%.

Ten years' service has confirmed their choice of lubricating oil to their full satisfaction.

(From the records of a western power and light company)
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Good oil helps to lower lubrication costs—not to raise them.

The entire lubricating and engineering facilities of the Vacuum Oil Company are at your service. Our men are prepared to work with your staff in locating operating economies and devising lubricating methods to make them effective. We ask you to get in touch with us.

NOTE: On request we will send you, without obligation, our authoritative treatises: "Steam Turbine Lubrication," "Hydraulic Turbine Lubrication." Write for your copies.

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duced voltage along the lead will cause a flow of current in the sheath circuit. There will be no outward manifestation of voltage, but there will be a flow of current whose magnitude depends on the diameters of the sheaths, the space between sheaths and the conductor current. The current-carrying capacity of cables is in general limited by the permissible temperature of the insulation at the hottest point, adjacent a conductor. This temperature rise is caused, 1—by the $I^2r$ loss in the copper, 2—the induced $I^2r$ loss in the lead sheath, if the sheaths are bonded, and 3—the dielectric loss in the insulation itself, which comes into play only in high-voltage cables. The permissible current-carrying capacity of a cable is figured so that the sum total effect of all these three losses is to produce a temperature not in excess of the permissible temperature. There should not be any danger of melting the lead sheath. If a conductor current is used which is large enough to cause a sheath current sufficient for such an effect, it is obvious that the insulation will be heated way above its permissible value, and the current rating will have to be reduced to avoid injuring the insulation. There are two ways of handling this problem in single-conductor cable. The lead sheaths can be bonded and usually grounded at the far ends, in which case there will be sheath losses but no sheath voltages. The sheath losses will reduce the permissible current-carrying capacity. On the other hand, the sheaths may be bonded and grounded at one end only. In this case there will be no induced sheath losses and there will be no reduction in current-carrying capacity from this cause. There will, however, be induced sheath voltages which may be dangerous to cables and to workmen, especially at time of abnormal conductor current, such as when the line is carrying a through short-circuit, the induced sheath voltage being proportional to the conductor current. The magnitude of all these effects can readily be calculated from a paper published in THE ELECTRIC JOURNAL, 1025, p. 366. In particular, the induced sheath current can be obtained by formula (30), and the permissible current-carrying capacity including the effect of sheath loss can be obtained by using formulas (24), (25) and (26). D. M. S.

2878—BULB RECTIFICATION—When alternating current is rectified, does the frequency double itself? If so, please explain. What happens to the half cycle which is not used when alternating current is rectified as with bulb or other such rectifier?

R. M. (MICH.)

There are three types of bulbs commonly used for rectification. The exact physical explanation of their operation is slightly different but the general principle of all of them can be explained by that of the pure electronic type. In such a bulb, current is carried by the flow of electrons from a heated filament to a plate, the essential characteristics being that electrons will not flow from the plate to the filament. Confusion sometimes arises as to the direction of flow due to the fact that an arbitrary definition of positive and negative was made before the true explanation of current flow was understood. In the case of a bulb, where the electrons flow from the filament to the plate, it must be remembered that electrons are negative electricity so that it is a negative current which flows from the filament to the plate, hence the positive direction of current flow is from plate to filament. The essential characteristic, however, is that current will flow through the bulb in one direction only. Hence, when alternating current is impressed on a pure resistance through the rectifier bulb, during one-half of the alternating-current cycle the current is limited only by the resistance of the external load plus the relatively small resistance through the bulb. During the other half cycle the internal resistance of the bulb is exceedingly high so that practically no current flows. The result is a wave of the type shown in Fig. (a). If a storage battery is used as load instead of a resistance, the counter—e.m.f. of the battery prevents current flow until the instantaneous value of

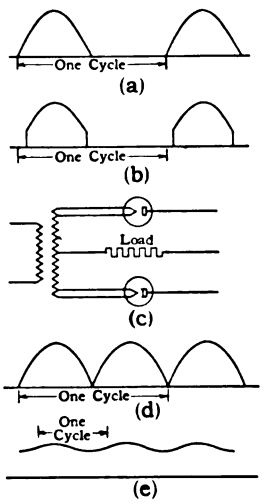


FIG. 2878

the sine wave exceeds that of the battery, giving a current wave of the type shown in Fig. (b). If two bulbs of this type are used connected so as to pass current in opposite directions as shown in Fig. (c), the effect is the same as if the negative half wave of the alternating current were turned over as shown in Fig. (d). If sufficient inductance is included in series with the load this wave will be smoothed out into something closely approaching direct current with a small alternating-current ripple superposed as shown at Fig. (e). It is readily seen that this alternating-current ripple is at double the frequency of the original alternating-current wave. Hence the general statement can be made that double bulb rectification gives a double frequency alternating-current ripple on the direct current; whereas with single bulb rectification the superposed ripple is of the same frequency as the original alternating-current wave. Some bulb rectifiers used for radio sets have two plates and one filament in the same bulb. The effect is the same as if two separate bulbs were used. C. R. R.

2879—TRANSMISSION LINE NO-LOAD LOSSES—It is desired to find the losses of a transmission system at no load. The system is about 350 miles in length. There are four transformers at the generator end, each 12 000 kv-a in capacity. Transformers are located at various points in the system. The distance between each transformer is known as a line section. The net charging current of each line section is known. The capacity of all transformers is known. If the line section farthest from the generating station is denoted as $A$, the next farthest as $B$, and etc., are the line losses figured as follows:—loss in $A = I^2_A R_A$, loss in $B = (I_A + I_B)^2 R_B$, and etc? How are the copper and iron losses in the transformers determined at no load? Are these losses doubled if two transformers are connected in parallel? How are these losses combined with the line losses, considering transformers to be located at various points along the system? What effect upon the line losses has a line section having two trunks in parallel?

E. T. A. (N.Y.)

The computation of the no-load losses of a transmission line is somewhat complicated, and any approximate method used will not apply universally to the many different conditions which must be met for different problems. The exact method used to determine these losses is too long and involved to be taken up here, but is completely covered in "Electrical Characteristics of Transmission Circuits" by William Nesbit, Chapter XV, "General Circuit Constants and Circle Diagrams". This chapter gives the formulas necessary for the determination of voltages, currents, power and losses, of any transmission line. If the line is complicated, that is, is made up of several sections, it is necessary to use reduction formulas to simplify before the losses can be determined, which makes the problem longer and more complicated. In case a line consists of several sections of approximately equal length, with transformers in each section of about equal rating, and the spacing of transformers is not above 20 to 25 miles; it is possible to introduce an approximation which gives very good results, and the work is materially shortened. This consists of assuming the impedance of the transformers as a distributed shunt admittance along the line, which is combined vectorially with the normal line shunt admittance, and the problem reduces to a simple line calculation. As mentioned above, any approximate method for determining the losses is only good for special conditions chiefly because of the errors introduced due to the shifting phase position of the charging current. However, this error becomes small if the line section being considered is not too long. The following approximation may be used providing the length of a section taken is not above 100 miles. The formula given is worked out on the basis that the voltage at any point of the section rises or falls between receiving and sending end according to a straight line law, which is not quite correct as the voltage-distance curve is usually slightly convex upward. However, the greater percentage of the error introduced is due to the shift in phase position of voltage and current along the line.

Let $E_r$ = Receiver voltage of section to neutral.
$E_s$ = Sending voltage of section to neutral.
$I_r$ = Receiver current of section.
$I_s$ = Sending current of section.
$R$ = Resistance of section.
$Y$ = Shunt admittance of section.

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Then $E_s = E_r\ (1 - K)$.

Where $K = \frac{E_r - E_s}{E_r}$

$$I_s = I_r + Y\left(E_r - \frac{K}{2}\right)$$

$$\text{Power Loss} = \left[Y^2 E_r^2 \left(\frac{1}{3} - \frac{K}{4} + \frac{K^2}{20}\right) + I_r Y E_r \left(1 - \frac{K}{3}\right)\right] R$$

In the above equations currents and admittance are vector quantities. The vector of reference is the receiver voltage. The equation is accurate to about 3 percent of the true losses for a 100 mile line and the error decreases with decrease in length of the section taken.

In the above equation if the receiver current is zero then

$$I_s = Y\left(E_r - \frac{K}{2}\right)$$

$$\textit{Power Loss} = Y^2 E_r^2 \left(\frac{1}{3} - \frac{K}{4} + \frac{K^2}{20}\right)$$

The no load losses of a transformer are best determined by test. The current in a transformer at no load is so small that usually it is assumed that there are no copper losses and the small copper loss is combined with the iron loss. The test is made by applying normal voltage to one winding of the transformer, and the losses are determined by a wattmeter in the circuit. The wattmeter is designed to be accurate at the low power factor which the transformer has at no load. If two transformers are connected in parallel the no load loss per transformer, remains the same, provided the impressed voltage on the transformer is still the same. If the transformers are at the receiving end of a transmission line the voltage with one transformer connected will usually be considerably different from the voltage with both transformers on the line. When transformers are connected to a line it consists in partially loading the line, which changes the voltages along the length of the line and changes the line losses. The problem of determining these combined losses when there are several transformers connected to the line is a complicated one. The method used is described in the chapter on general circuit constants and circle diagrams, already referred to. With two lines in parallel the no load losses are approximately doubled. B. V. H.

2880—High-Speed Dry-Battery-Operated Motor—Could a small electric motor be made that would run on a six-volt hot-shot dry battery and produce 1/6 hp and a speed of over 2000 revolutions per minute?

A. A. N. (IND.)

A 1/6 hp motor operating at 2000 r.p.m. and designed to operate from a six-volt source of energy can be built. The full-load current of a 1/6 hp six-volt motor will be approximately 32 amperes. Since a dry battery will supply only two or three amperes for any appreciable time and 6 to 8 amperes on an intermittent service such as ignition, it will not be satisfactory for operating a motor which has a full-load current of 32 amperes. The short-circuit current of this battery will probably not exceed 35 amperes. It will require 20 or 25 such batteries in parallel or a total of over 100 to have sufficient current capacity to operate a 1/6 hp motor. Even so, the life of the batteries would be very short. F. C. D.

2881—Blowing of Fuses—Kindly explain the cause of a 30 ampere fuse blowing out when a 15 ampere fuse that is in series with it and carrying some current remains uninjured. This has happened on 110 volt circuits on several occasions. J. E. W. (QUEBEC)

Fuses are rated at the current which will cause them to open a circuit when the current is slowly increased. This gives time for adjacent masses of metal to assist in conducting the heat away. On the other hand in the case of a very heavy short-circuit there is no time for the heat to be carried away from the place where it is produced by the $I^2R$ loss. Under this condition the fuse which will survive longest is the one which has the greatest inherent heat storage capacity at the particular part of the fuse where the temperature is highest. Thus it is entirely possible to have a fuse which will blow on 15 amperes current continued for sometime and yet which will hold on longer than a 30 ampere fuse of different construction on a very heavy short-circuit. It is obvious that either of the fuses would blow on the heavy short-circuit if it were not that the first one to blow out interrupts the circuit. If the time current characteristics of the two types of fuses be plotted as shown in Fig. (a), these curves represent the condition that the 15 ampere fuse has greater heat storage capacity at the place where it melts and will consequently hold on longer at a very high current than the 30 ampere fuse which has small heat storage capacity but much larger heat radiating capacity. Such a characteristic would probably result if the 15 ampere fuse were a straight piece of ribbon as shown at (b) and the 30 ampere fuse were a heavy piece of ribbon with v's cut out of the middle as shown at (c). The fuse at (c) would probably blow out quicker on a very heavy overload than that at (b); whereas, that at (b) would probably blow out with a smaller current if there were only a slight overload continued for a long time. C. R. R.

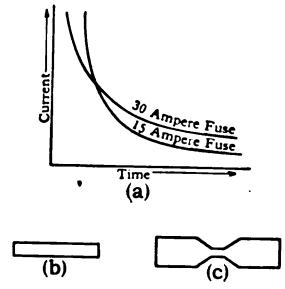


FIG. 2881

2882—Effect of High Voltage on Laboratory Instruments—We are contemplating the erection of a brick building whose walls will be within ten feet of the foundations for high tension bus supports carrying 120 000 volt, 60 cycle current. The nearest bus will probably be about 25 feet distant from this building which is intended to contain our chemical and metallurgical laboratory equipment. The question arises, what effect, if any, will the close proximity of high tension equipment have on the delicate laboratory instruments, scales, galvanometers, pyrometers, etc.

W. A. S. (OHIO)

If it is possible to relocate the laboratory so as to avoid such close proximity to the high-tension wires, it would certainly improve the operating conditions of such a laboratory. If the laboratory must be located within that distance of the transmission lines, a certain amount of screening can be secured by the employment of a double wall of copper fly screen mounted upon a wooden structure with each of the two screen walls insulated from the other and the outer one of these grounded. A certain amount of freedom will be afforded by this from magnetic disturbances but not as great as for the electrostatic effects. It will be necessary in such a structure to have the windows and doors provided with suitable netting so as to make the enclosure complete. The order of the effect on the several instruments employed will depend largely upon the sensitivity of the instruments. S. M. K.

2883—Noise From Lightly Loaded Alternator—A 10 000 kv-a, 50 cycle, three-phase, 5000 volt, 80 percent power-factor, 60 degrees rise temperature alternator makes grunting noise during light load period when it carries only about 20 percent of its rated load. During this period it is noticed that if the load either increases or decreases by 5 percent, due to traction demand the machine makes peculiar grunting noise. Nothing abnormal is found on this machine. Normally it runs hotter than other machines by ten degrees as its ventilation is not so good. It is located centrally in the power house and draws less air than other machines. Do you think the noise has something to do with the ageing of laminations due to the machine running hot? At 75 percent load the temperature of the machine is 75 degrees C. which is ten degrees higher than on other machines.

J. A. S. (INDIA)

Noise is generally caused by magnetic pulsations within the machine. The magnitude of these pulsations depends upon the extent to which various parts of the machine resonate with them. There is no apparent reason why the 10 000 kv-a, three-phase machine is noisy when delivering a balanced, three-phase load of 20 percent plus 5 percent is indicated. The noise is undoubtedly not what is considered purely magnetic as this noise is usually amplified with increase in the field strength or load and would be more noticeable at full load than 20 percent load. It is possible that the increase in load due to traction demand, is a single-phase load, in which case, there may be some mechanical vibration of the frame with a period low enough to give this so-called "grunting noise". The noise is without question independent of ageing of the iron. The degree of ageing of the iron is usually very small and its only effect might be a slight increase in the core or iron loss in the machine. The main reason, undoubtedly, for this machine running hotter than other machines in the power house, is due to the ventilating conditions surrounding this machine. Probably this machine is recirculating much of its own discharge air if the power house is not well-ventilated. To reduce the rise of this machine, an attempt should be made to better ventilate the station. A. M. G.

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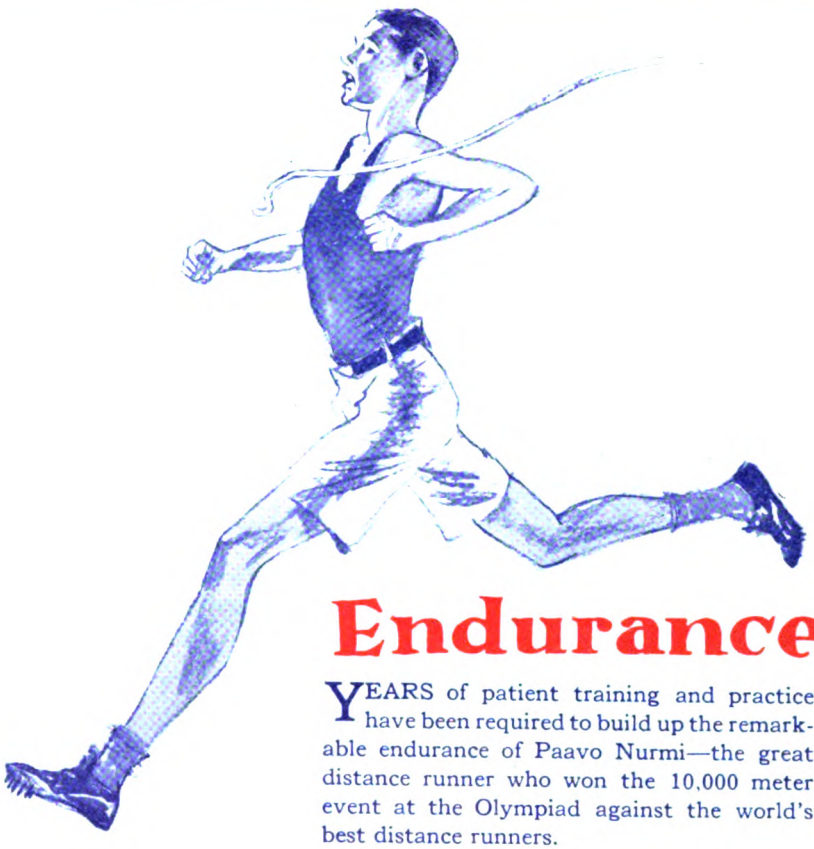

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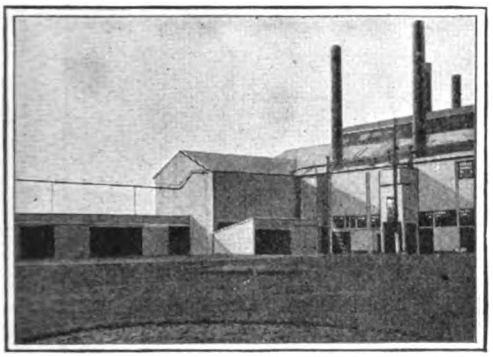
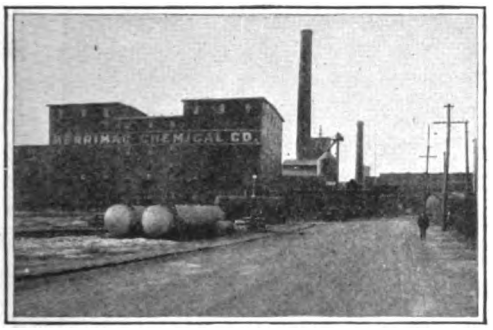
# Fuller Lehigh Products are meeting the varied demands of industry in Pulverized-Coal Firing



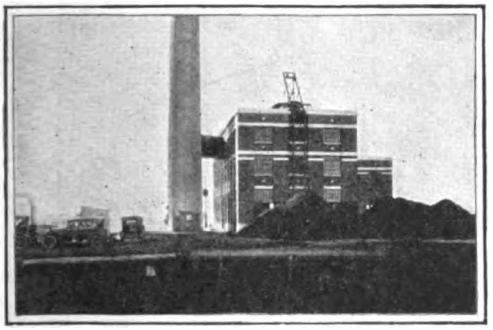
## —at Central Iron and Steel Company

The Fuller Lehigh storage system of pulverized-coal firing was adopted as offering the greatest opportunity for reducing the cost of plate-mill furnace operation. Coal is pulverized in a central pulverizing plant and transported like a fluid through an outdoor uncovered pipe line exposed to all weather changes. The installation resulted in lower fuel and labor costs, greater flexibility, cleaner products, increased output per furnace, lower furnace maintenance and no ash handling problem.



## —at Merrimac Chemical Company

They replaced stoker fired units with modern Fuller Lehigh direct-fired Pulverized-Coal equipment for power and process work *without alteration of the boiler-house structure or increase of space required.* Boiler efficiency has increased from 65 per cent to 80 per cent, with greater flexibility and a reduced operating force.



## —at Detroit City Gas Co.

Reliability of service and flexibility of design were factors of great importance in the selection of equipment for this gas-booster station.

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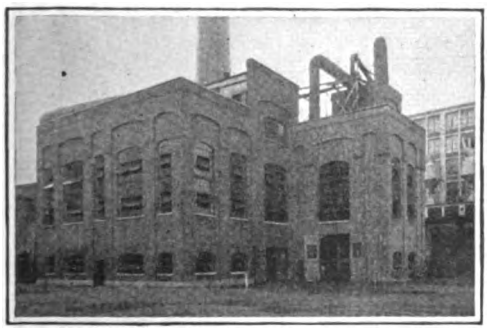

## —at Goodall Worsted Company

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# TABLE OF CONTENTS FOR DECEMBER, 1928

## EDITORIALS


Air Ejector Selection for Surface Condenser Installations.....*C. B. Tuley*..... 573

Standardization of Electrical Measuring Instruments.....*P. MacGahan*..... 573

Balancing in the Field.....*Chas. R. Riker*..... 574


## ARTICLES


Standard Line of Direct-Current Machines Fabricated By Arc Welding.....*R. S. Marthens, C. C. Brinton, and F. T. Hague*..... 575

The Operation of Direct-Current Motors in Parallel and Series With Different Types of Load.....*C. T. Pearce*..... 581

The Development of Enclosures for Synchronous Converters..*R. H. Newton*..... 586

Apparatus Used in the Investigation of Lightning Phenomena..*Edward Beck*..... 591

Field Balancing of Rotors.....*James J. Ryan*..... 596

Surge Voltages Produced by Direct-Current, Air, Circuit Interrupters.....*Leon R. Ludwig*..... 604

Methods of Testing Electrical Apparatus—XXIX—Three-Phase Transformers..... 608

The Use of Steel in Switchboard Designs.....*T. A. Kenny*..... 613

How and Why..... 615

The Journal Question Box..... 619


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# The sign of success

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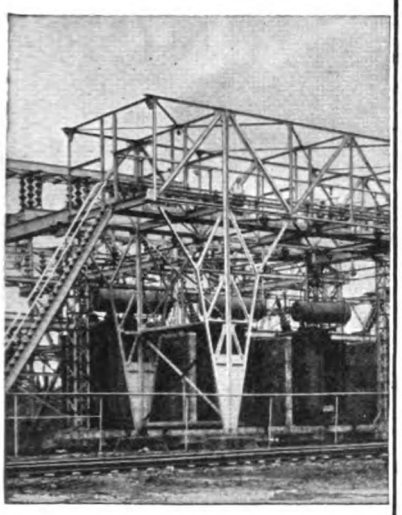

General view of the Essex 132 K. V. Outdoor Substation of Public Service Electric and Gas Company, designed and constructed by Public Service Production Company, Newark, N. J.

The secondary leads consist of three 3¼" O. D., 2¾" I. D. Anaconda Copper Tubes per transformer bank, spaced on 2'6" centers; length of space between insulator supports, 20 feet.

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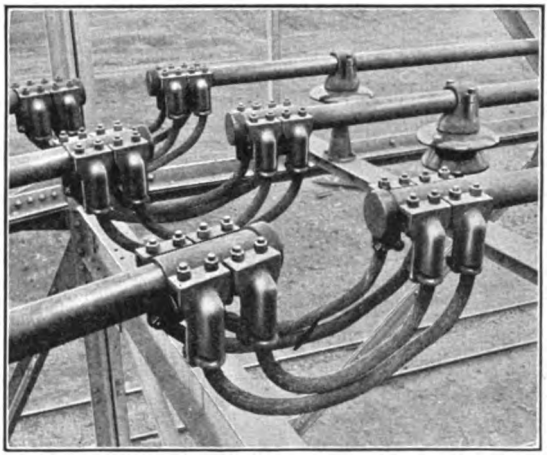

Detail of angle expansion joint.

# Anaconda *high conductivity* Bus Tubes

TUBULAR conductors are more efficient for large alternating currents than solid conductors because of the tendency of the current to crowd itself away from the center of the conductor. This effect is especially noticeable above 2,000 amperes at 60 cycles and for smaller currents at higher frequencies.

The tubular shape is ideal for mechanical rigidity in all directions. Hard drawn copper tubes are more rigid and have higher tensile strength than soft drawn tubes, thus raising the yield point, but up to the yield point, sag is independent of tensile strength.

Anaconda high conductivity bus tubes have a minimum conductivity of 98% when hard drawn and 99% when annealed (hard drawn tubes are standard and will be supplied unless otherwise specified).

Bus tube connections are usually made with bolted or soldered fittings, but some engineers prefer to flatten the ends and join with bolts. Anaconda high conductivity tubes will flatten cold without cracking if finished soft or with a light draft.

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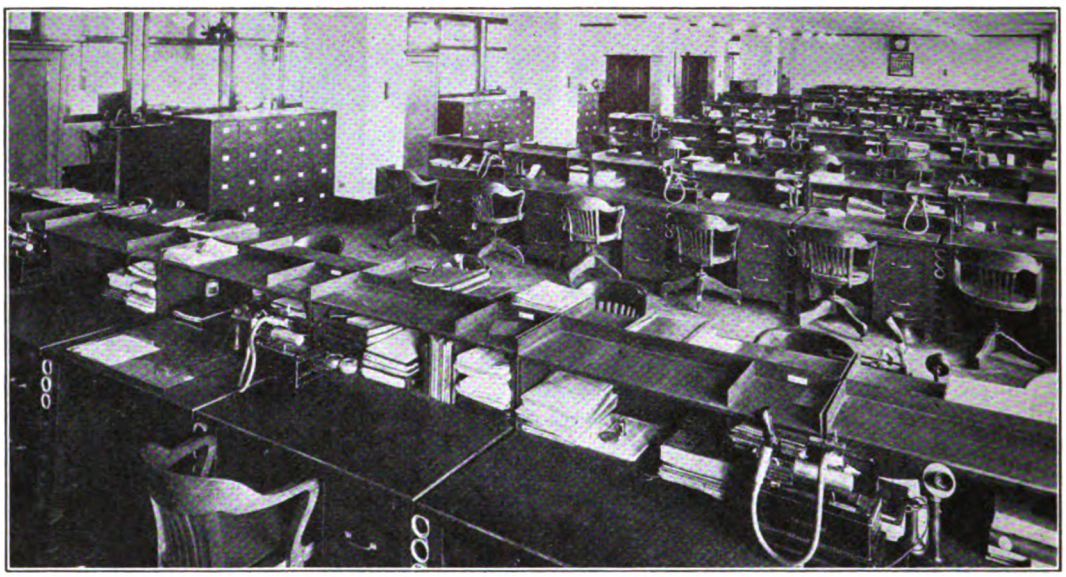
# DESIGNED FOR CONVENIENCE

In the Chicago District office of the Westinghouse E. & M. Co. the salesman's room was crowded with 69 wooden desks.

Here is a picture of that same room, furnished with

## *88 Jamestown Metal Desks*



No crowding—every desk especially designed for the salesman's comfort and convenience—having a shelf built across the back of each desk, and a built-in mail basket.

The drawer arrangement provides two large letter drawers in one pedestal, and dictaphone cylinder space between the desks.

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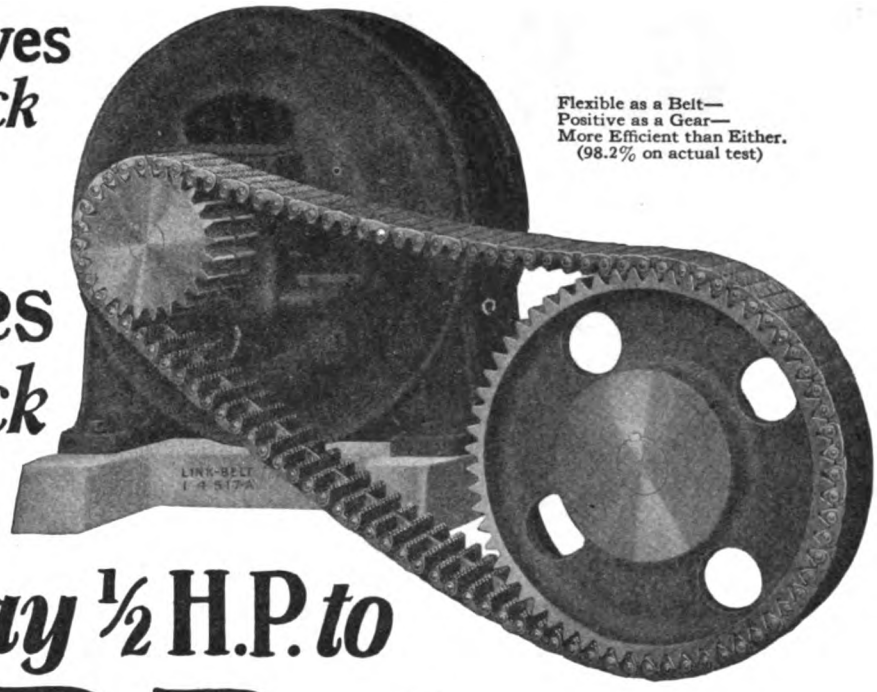


# *and today* ½ H.P. *to* 60 H.P. Drives *from Stock!*

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The demand for Link-Belt Silent Chain Drives has been increasing so rapidly that now they can be obtained from Link-Belt stocks, or from distributors throughout the United States, in sizes from ½ H. P. to 60 H. P., and in speed ratios of 1 to 1 up to 7 to 1.

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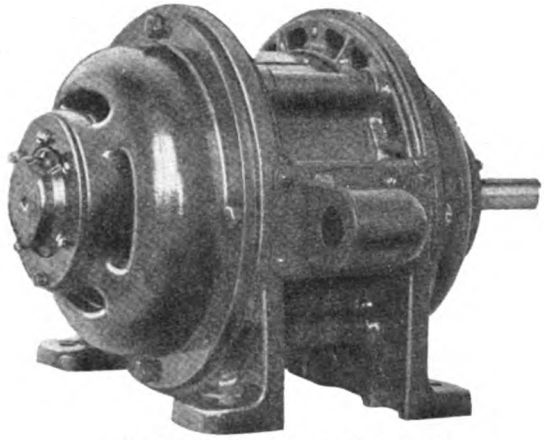
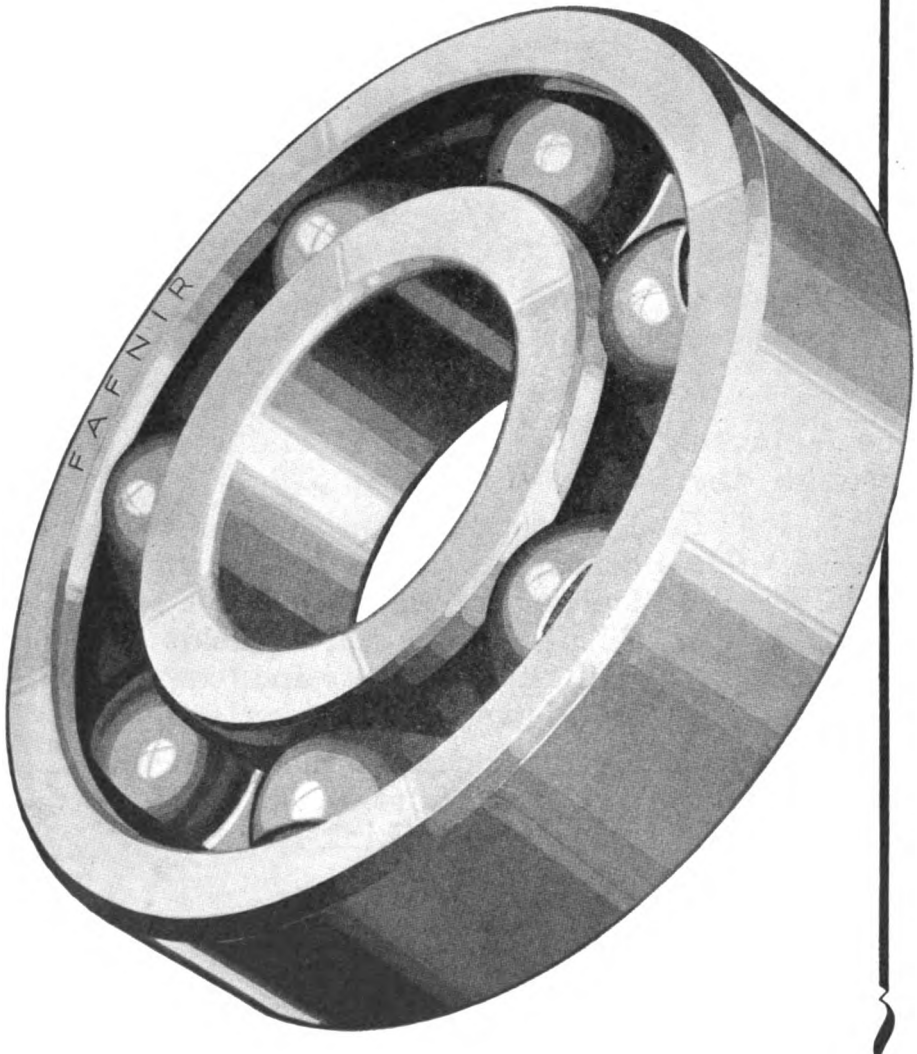
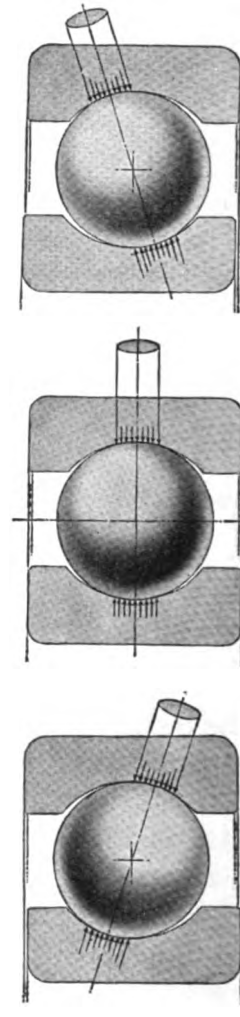


"900 Series" Ball-bearing Motor with Cartridge-type Housing




**The Ball Bearing Principle means greater capacity**



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## BALL BEARINGS

BALL BEARINGS IN AMERICA



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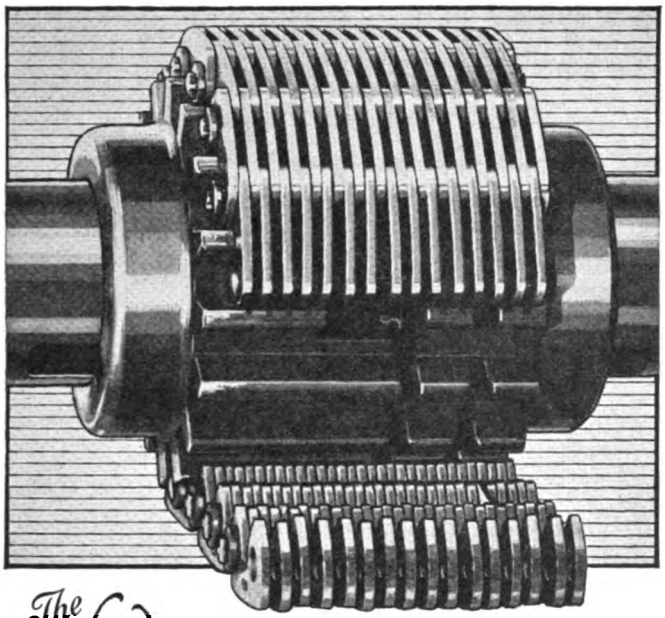

The New MORSE Flexible Coupling

Simplicity is the keynote in the design of this new Morse Flexible Coupling. It consists merely of a Morse Silent Chain encircling two sprockets as shown. The guide groove in one sprocket holds chain in place while the other sprocket is free to float under the chain. The chain fits loosely enough on the sprocket to take care of ordinary misalignment.

Simple design combined with the high efficiency and long life for which Morse Chains are noted, provides a coupling ideal for most requirements. Fill in the coupon for complete data.

See the Morse Flexible Coupling on exhibit in Booth 264 and one half of 263 at the Seventh National Exhibition of Power and Mechanical Engineering, Grand Central Palace, New York, December 3d to 8th.

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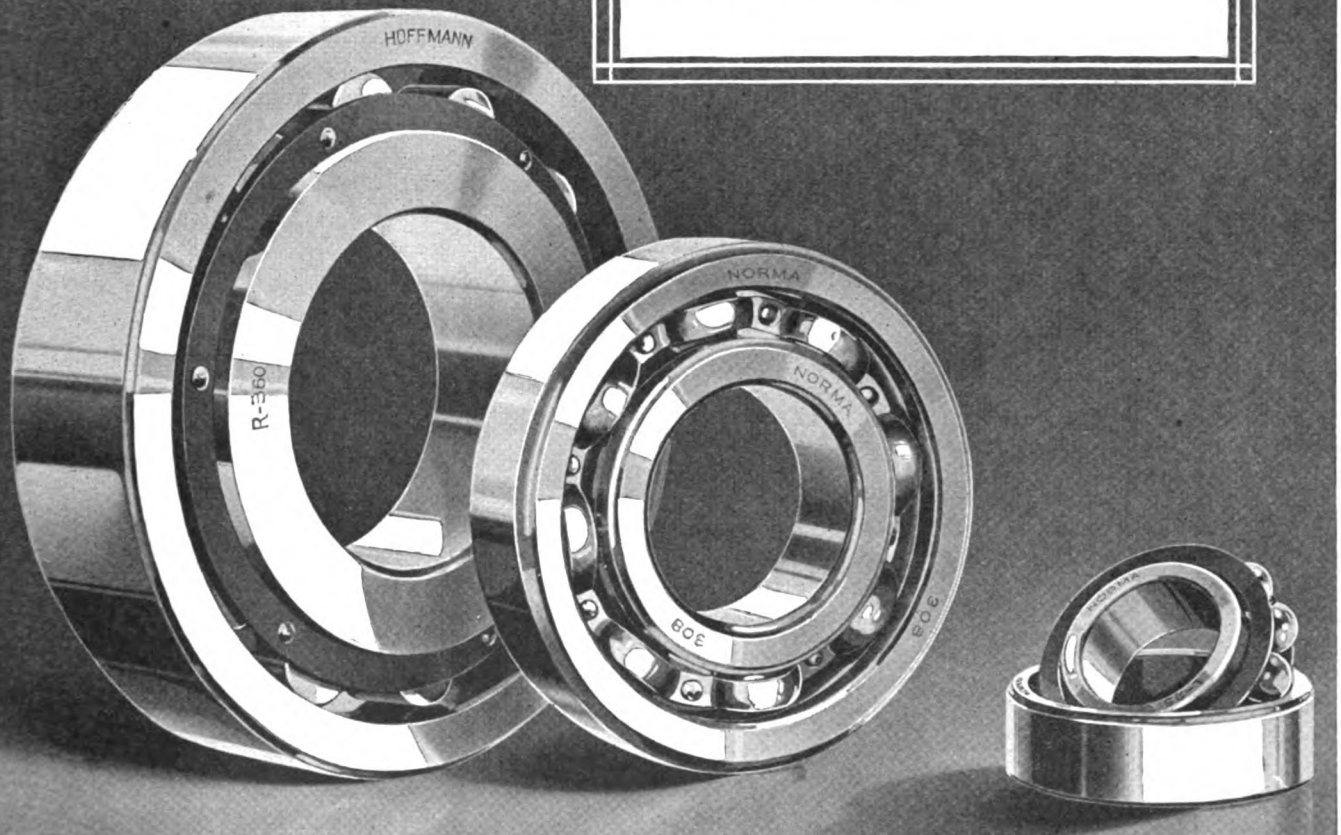


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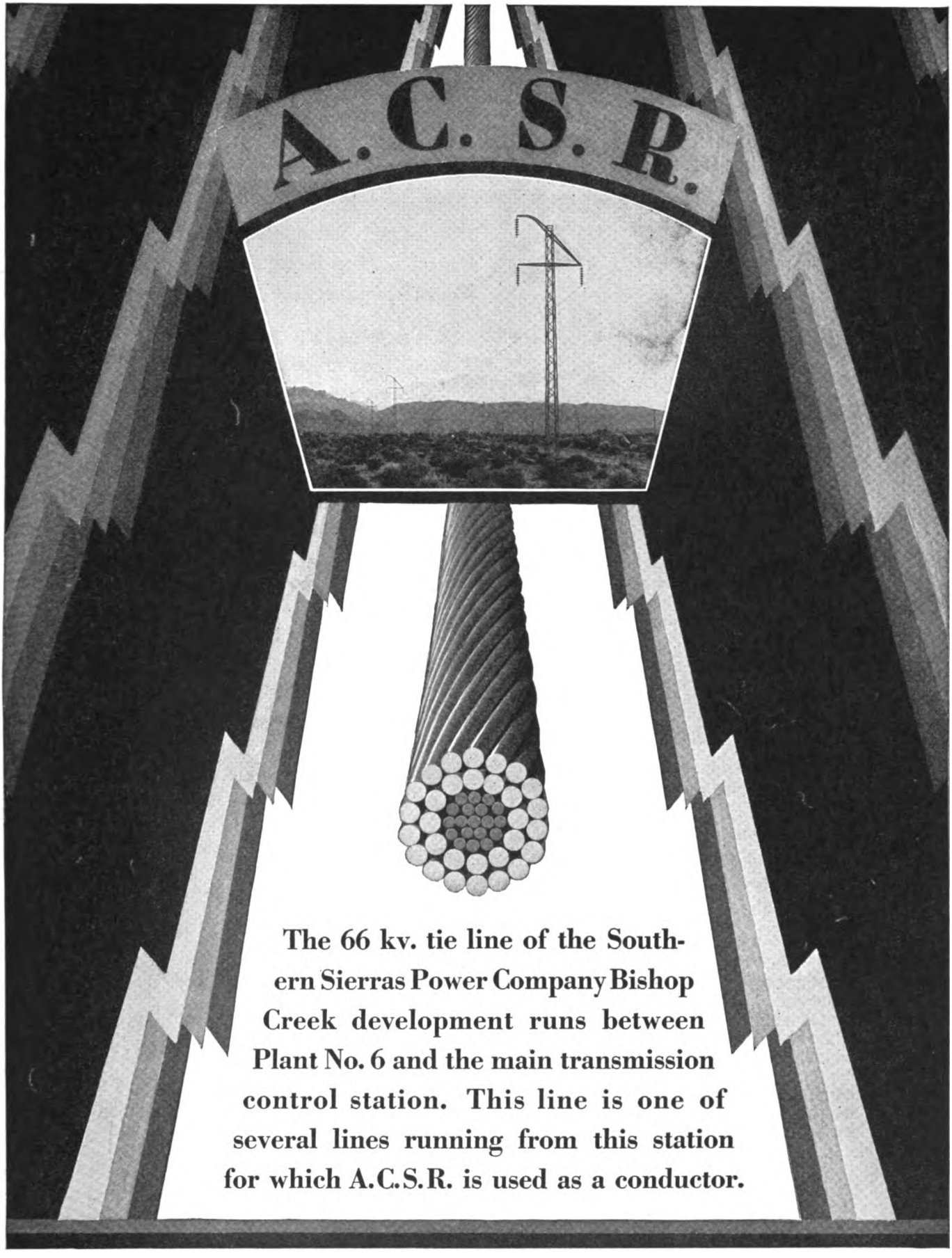


The 66 kv. tie line of the Southern Sierras Power Company Bishop Creek development runs between Plant No. 6 and the main transmission control station. This line is one of several lines running from this station for which A.C.S.R. is used as a conductor.

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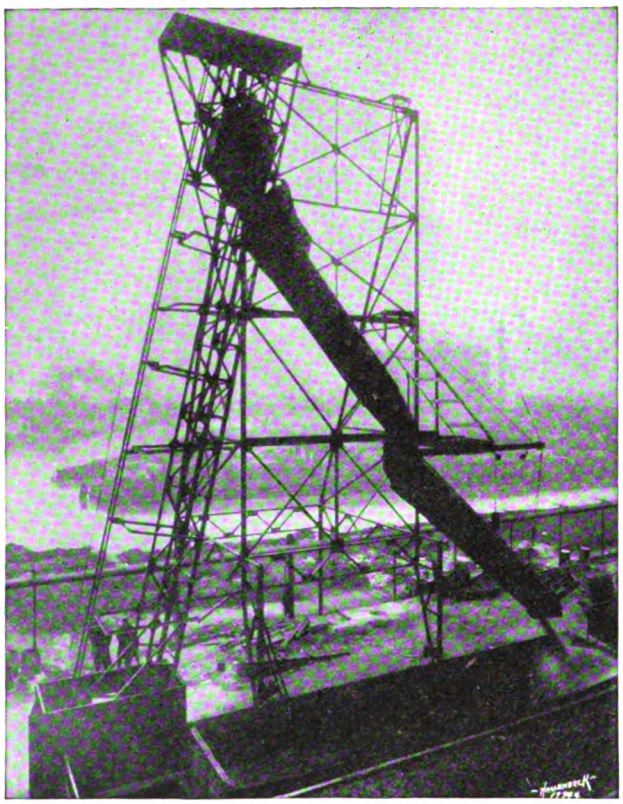

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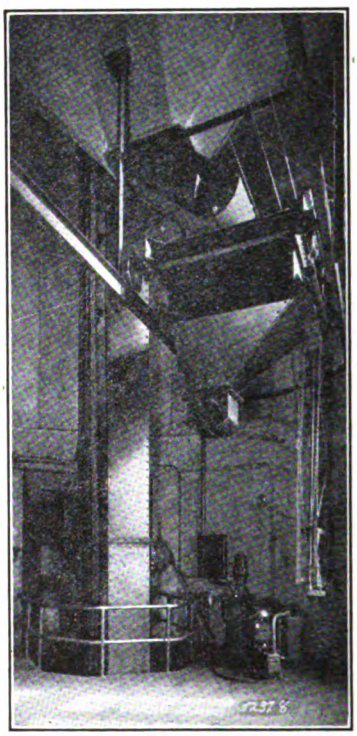

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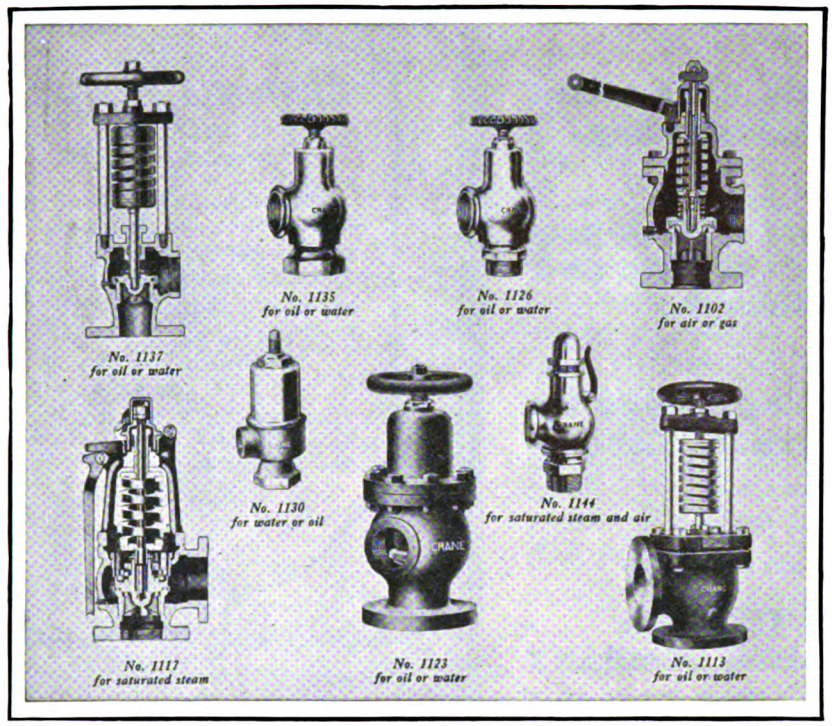


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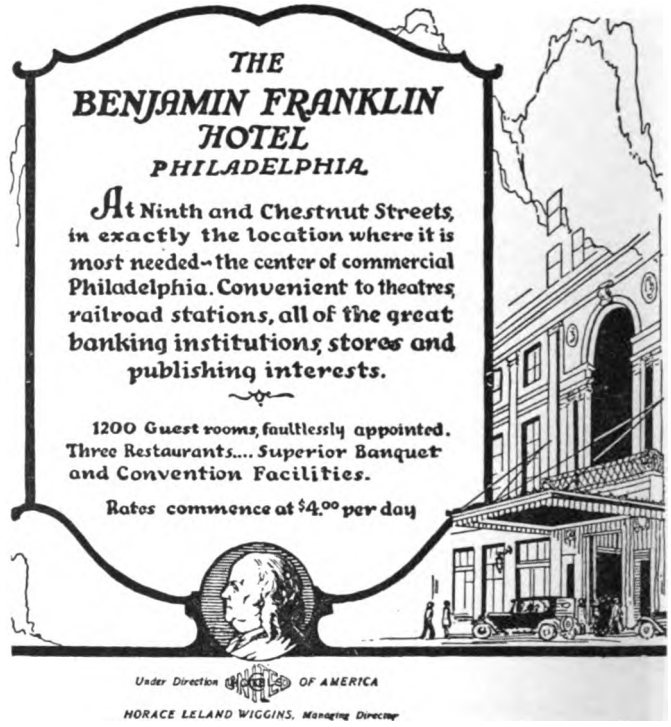

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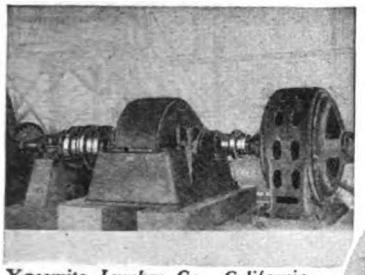

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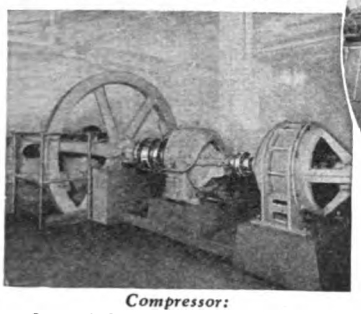
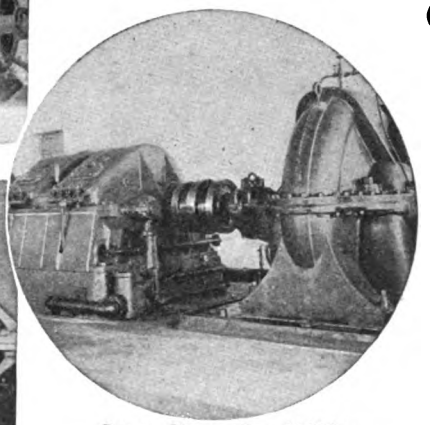


Compressor:
General Motors Building, Detroit



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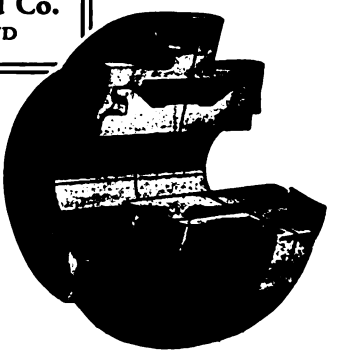

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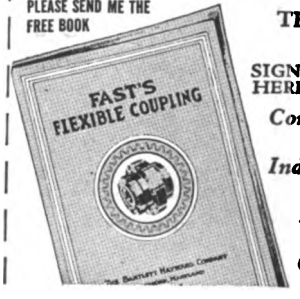


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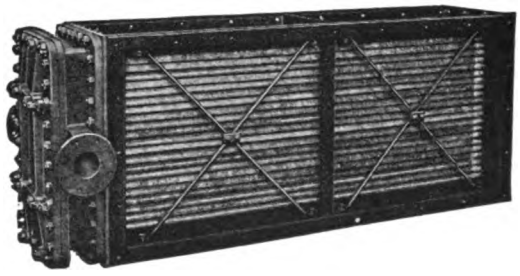

1—*Patent Multipass water head*—the cooling water is properly distributed for most effective action.

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3—*Convenient tube removal*—each pair of U-fin tubes can be withdrawn without removing adjacent tubes.

4—*Special water box construction*—design permits easy inspection of tube interiors.

5—*Condenser type water head*—tube ends can be examined without interfering with duct work or water connections.

6—*No brazed or ferruled joints*—all tubes are expanded into tube plate and return bend, and tubes and return bends are tinned externally.

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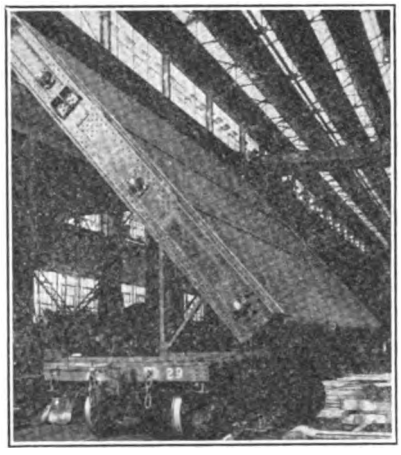

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## *the Flood of the Susquehanna River is controlled by*

## 50 Newport News Crest Gates

Each gate is 40 ft. wide by 22 ft. 6 inches high and weighs 42 tons. They were completely assembled at the Newport News plant and shipped by barge to Port Deposit, Maryland, thence to Conowingo on special cars. The details of this shipment constituted an engineering feat in itself because of the tremendous bulk of these gates.

The total weight of the Newport News Equipment at the Conowingo Dam is 5,463 tons.

*Additional Newport News Equipment at Conowingo*

3 Regulating Gates
1 Service Gate
4 Sectional Head Gates
2 Station Service Head Gates
40 Stop Logs
8 Stop Log Seals
1 Mechanical Rack Rake
1 Station Service Stop Log
8 Draft Tube Stop Logs
70 Racks
28 Rack Frames
2 Station Service Racks
4 Station Service Rack Frames
Guides for Above Equipment

*Hydro-Electric Division*

NEWPORT NEWS SHIPBUILDING AND DRY DOCK CO.

Newport News, Virginia — Charlotte, N. C. — New York, N. Y., 232 Broadway




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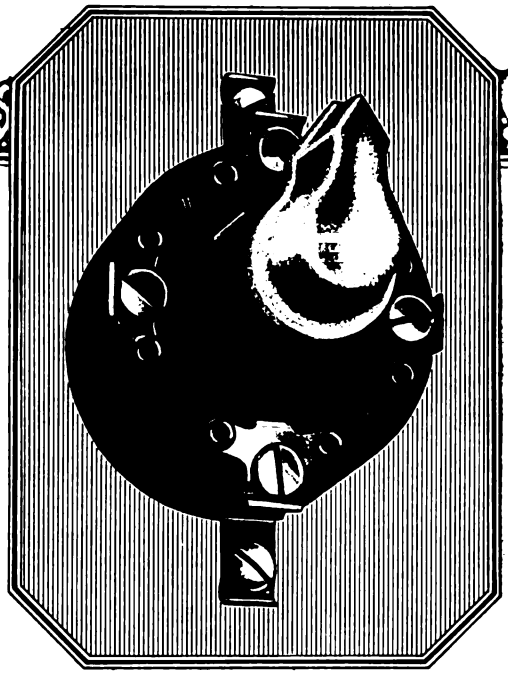


"Diamond H" Load Balancing Switch, Round base type.

# Naturally They Chose "DIAMOND H" Load Balancing Switches!

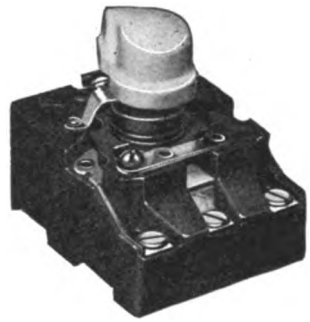
Central Stations realized the value of balancing the electric range load.

Range manufacturers were quick to help Central Stations meet this problem.

They instinctively turned to "Diamond H" for the answer and it was ready.

"Diamond H" Load Balancing Switches are ready in all types to meet the requirements of the range manufacturer, and that is why a large percentage of range manufacturers chose "Diamond H" Switches, and the country's best electric ranges are now equipped with them.

"Diamond H" Heater Switches are superior, both in design and mechanical operation. A high standard of manufacturing is always maintained.



Load Balancing Switch Block Type for bus bar mounting

THE HART MANUFACTURING CO.
HARTFORD, CONN.

NEW YORK BOSTON CHICAGO TORONTO

DIAMOND H SWITCHES



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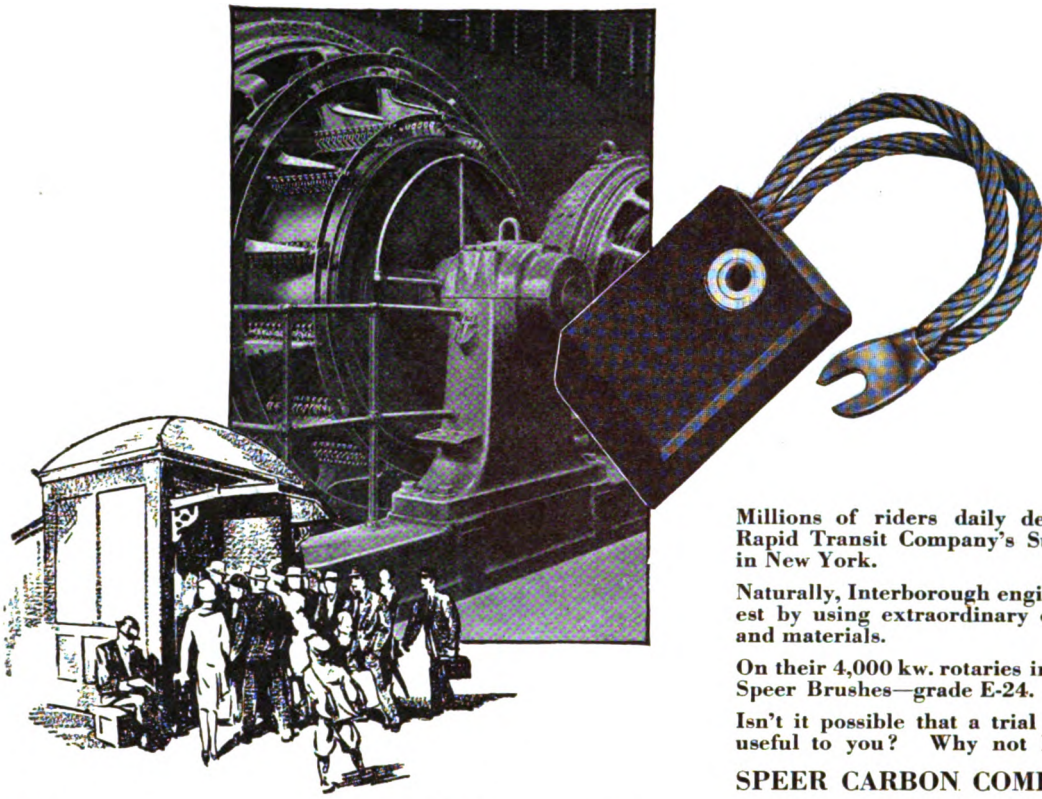


## New York's Subway!

Millions of riders daily depend on the Interborough Rapid Transit Company's Subway and Elevated service in New York.

Naturally, Interborough engineers guard the public interest by using extraordinary care in choosing equipment and materials.

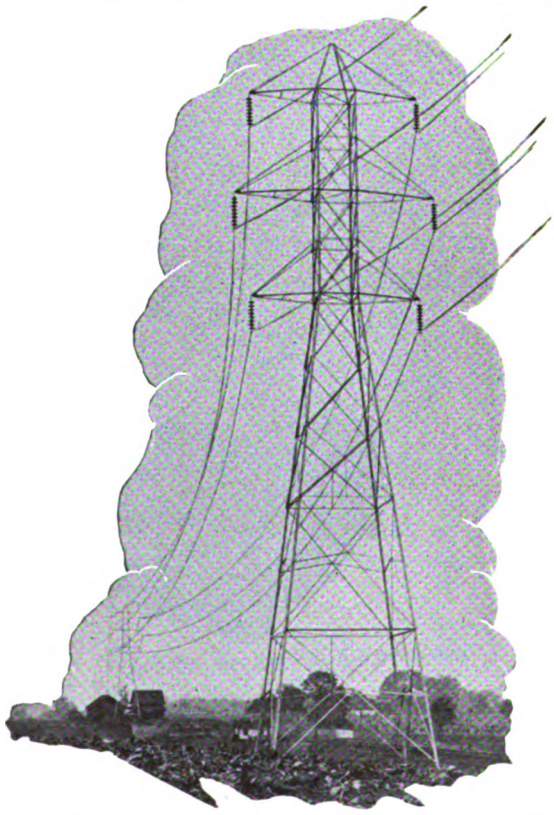
On their 4,000 kw. rotaries in I.R.T. substations, they use Speer Brushes—grade E-24.

Isn't it possible that a trial of Speer Brushes would be useful to you? Why not let's discuss arrangements?

SPEER CARBON COMPANY, Saint Marys, Pa.

# Speer Carbon Brushes

2568 R



# BLAW-KNOX TOWERS

Philadelphia—Emilie Line of the Philadelphia Electric Company for 132,000 volts; present operation 66,000 volts. 477,000 c.m. A. C. S. R. conductors, 1,000 ft. normal span. Standard Tangent Suspension Tower. Erected on Malone Anchors.

## Blaw-Knox Co.

Pittsburgh, Pa.

*Manufacturers of Blaw-Knox ELECTRO-FORGED Steel Grating and Flooring*

TRADE MARK BLAW-KNOX

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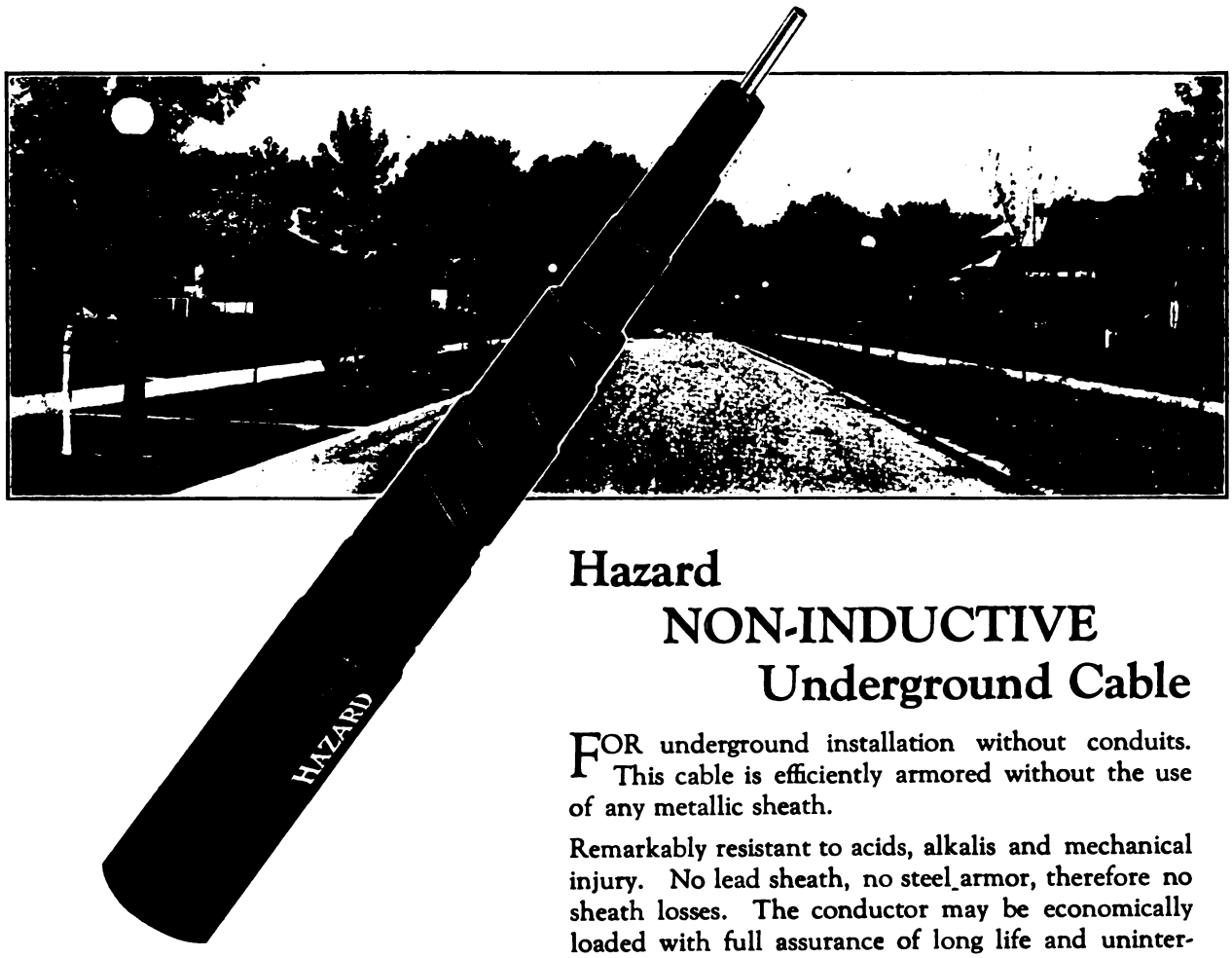
HAZARD

*an armored cable for 20 ampere street lighting circuits*




## Hazard NON-INDUCTIVE Underground Cable

FOR underground installation without conduits. This cable is efficiently armored without the use of any metallic sheath.

Remarkably resistant to acids, alkalis and mechanical injury. No lead sheath, no steel armor, therefore no sheath losses. The conductor may be economically loaded with full assurance of long life and uninterrupted service.

Its light weight saves freight and handling charges and makes it easy to install.

Send for sample and complete information.

Hazard Parkway Cable may be purchased from any Westinghouse District Office or Agent-Jobber. They will gladly supply any desired information either on Hazard Cable or on complete lighting installations

## HAZARD INSULATED WIRE WORKS

Division of The Okonite Company

WORKS: WILKES-BARRE, PA.

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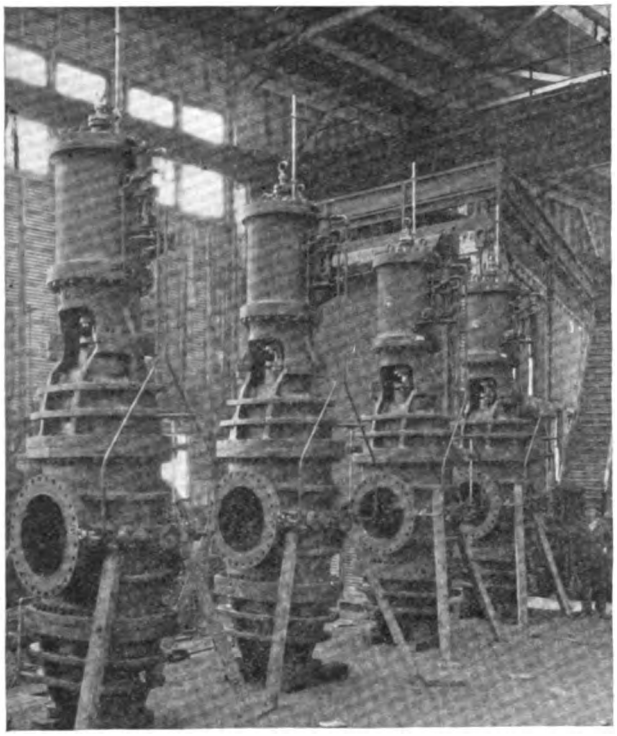
PELTON



# Record Static Head at Buck's Creek Plant

The Pelton hydraulic cylinder-operated gate valves shown are installed in the Buck's Creek Plant of the Feather River Power Company in California under 2612 ft. head, the highest static head yet developed for a large capacity water wheel installation. They were furnished as auxiliary equipment for two 35,000 Hp. Pelton double overhung water wheel units.

These valves are of the follower ring type to provide a smooth bore through the valve body when in the full open position and thus eliminate the head losses due to change of area at this point. The valves are remotely closed from the switchboard, hand control being provided for opening at the valve as an operating safeguard.

**All Pelton valves are described in bulletin No. 28. Copies sent on request.**

**THE PELTON WATER WHEEL COMPANY**

***Hydraulic Engineers***

**2987 Nineteenth St., San Francisco 100 Broadway, New York**

**Associated Companies: I. P. Morris Corporation, Philadelphia; Dominion Engineering Works, Ltd., Montreal**

PELTON

# Moloney Transformers

***Every Installation Fully Demonstrates Moloney Quality***

High quality performance has been identified with the name Moloney over a period of thirty years. During this time we have applied our complete efforts, time and experience to giving industry better transformers.

***Complete information furnished upon request***

**Moloney Electric Co. - St. Louis, Mo.**



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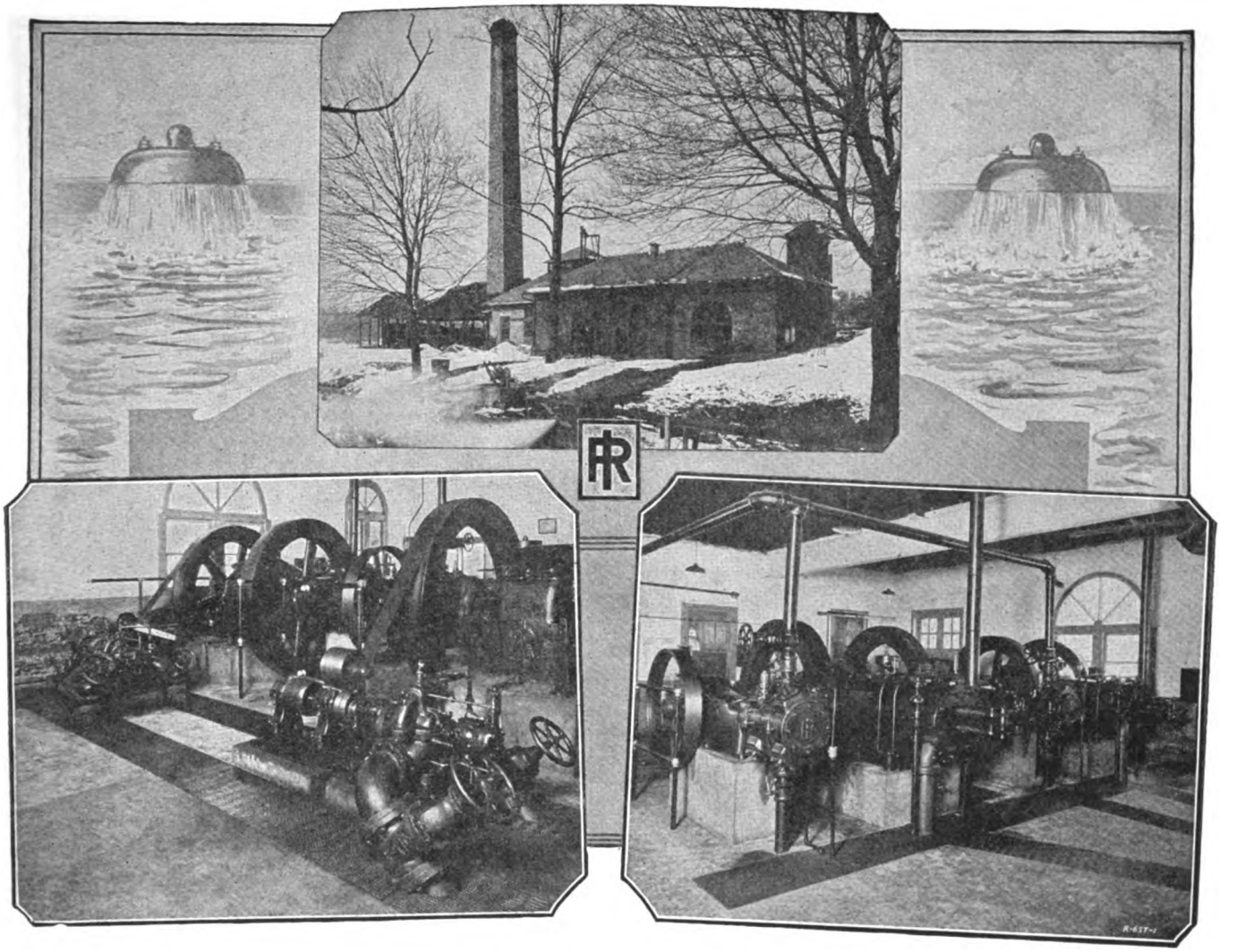

# *Diesel Engine Pumping Plant Saves 74% in Operating Costs*

**The Borough of Freehold, N. J., uses an air lift pumping system in the municipal water works. The main units consist of Ingersoll-Rand Diesel Engines direct-connected to I-R Compressors. These engines also belt-drive Cameron Pumps.**

**Recently, a motor-driven emergency unit was installed as stand-by equipment to eliminate the danger of a complete shut-down. For comparison in operating costs, this emergency unit was placed in service for one month. The power cost was approximately $500.**

**The monthly operating cost of the Ingersoll-Rand solid-injection Diesel engine equipment, pumping the same quantity of water, is approximately $130—a direct saving of 74%.**

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For Canada Refer—Canadian Ingersoll-Rand Co., Limited, 10 Phillips Square, Montreal, Quebec.

# Ingersoll-Rand

141 S. O. E.



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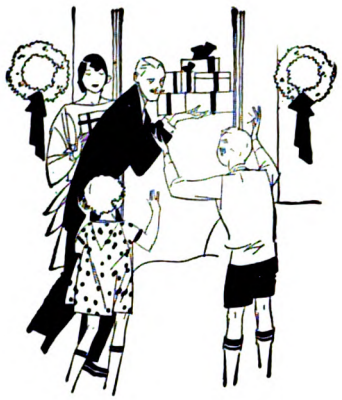


## "We opened our presents right after breakfast"

This is *our* home for the holidays! Mary wanted to get away over Christmas—she deserves a rest—and this was more like home than any place we knew of. . . . We had a great Christmas here last year. There were all sorts of decorations around, a big tree where the children opened their presents, and the people as pleasant and happy as they always are here. . . . They waked us Christmas Day with carols—in a hotel! I don't think I ever said Merry Christmas so many times as I did that day. And I never felt more like saying it than after the Christmas dinner! . . . We're mightly glad to be here again.

* * *

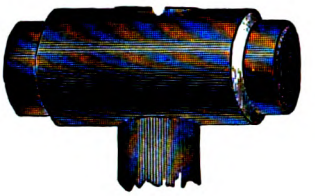
*Reservations for the holidays should be made at an early date. . . . May we send you a booklet, completely describing Chalfonte-Haddon Hall?*

CHALFONTE-HADDON HALL

ATLANTIC CITY

*American Plan*

LEEDS AND LIPPINCOTT COMPANY



# RAW HIDE

We have used this heading, wondering if you would be sufficiently interested to read about what we are making

**In purchasing or using a Hide Faced Hammer or Raw Hide Mallet, probably very few understand the care used in selecting and preparing the Hides, which is the first step necessary to insure a satisfactory and service-giving article. Then comes the manufacture of the Hide into the following products:**

*Hide Faced Hammers*

*Raw Hide Mallets*

*Raw Hide MALLETS LOADED*

**Made from Raw Hide and By Us**

# Holbrook Raw Hide Co.

Providence, R. I.

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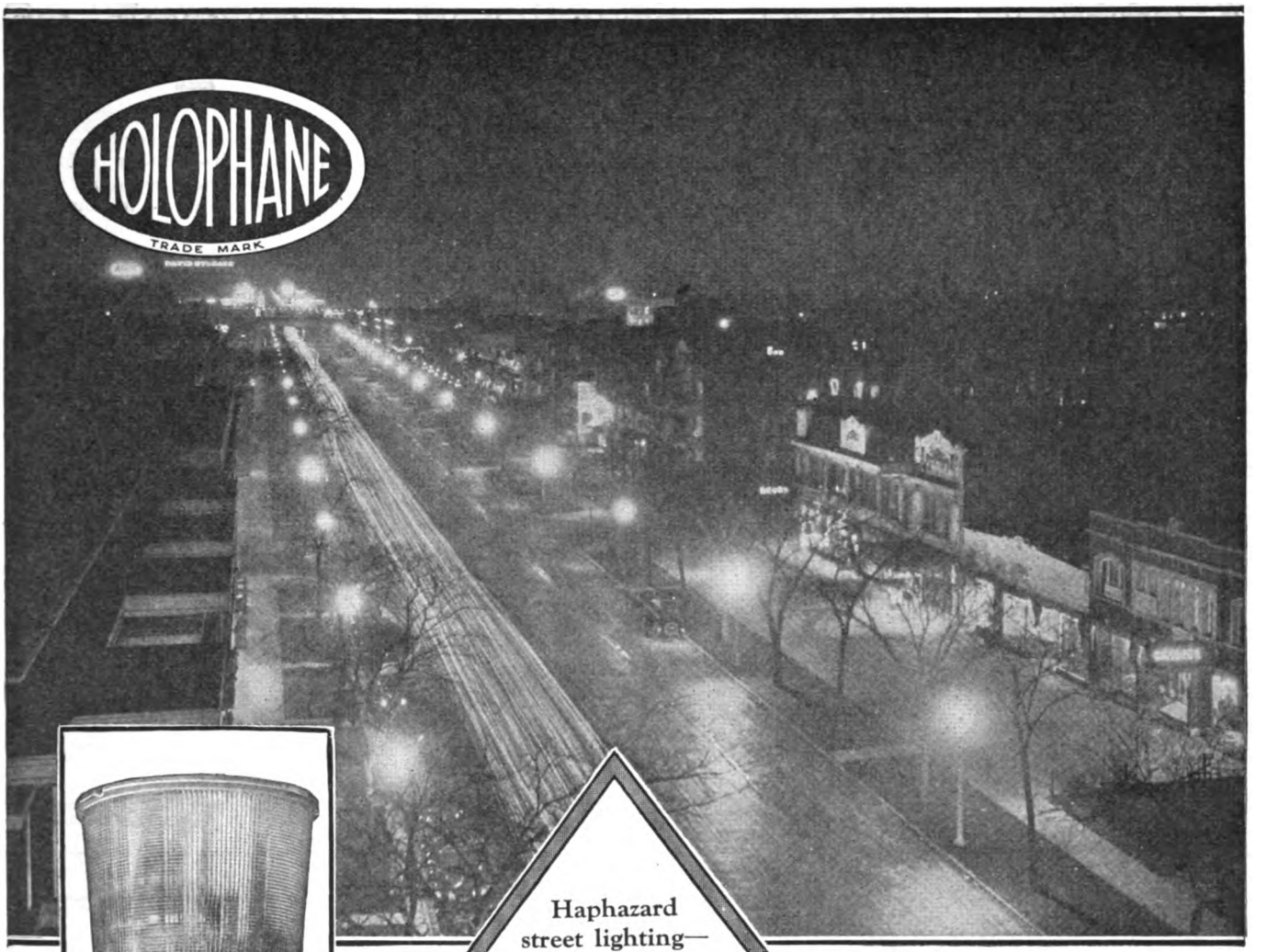

The illustration at the left shows the Holophane BI-LUX refractor which is one of the many different types in the Holophane line. This refractor is a Holophane specific for increasing the effectiveness and efficiency of ornamental street lighting.

PLANNED LIGHTING

Haphazard street lighting—lights strung or set along streets or highways by guess-work or rule-of-thumb—is never efficient and seldom effective.

Such lighting often results in glare, in dark areas between lamps, in wasted current and in high costs of installation and maintenance.

Holophane street lighting is efficient. It is the application of Holophane Refractors in accordance with the fundamental principles of Scientific Street Lighting. Such cities as Cleveland, Detroit, Milwaukee, Minneapolis, San Francisco, Los Angeles, New Orleans and many others use Holophane Street Lighting.

For further particulars, for data on specific installations, for lighting recommendations for streets, parks, bridges, highways, etc., get in touch with the Street Lighting Engineers of the General Electric Company, the Westinghouse Company, the Line Material Company or the Holophane Company, 342 Madison Avenue, New York.

**HOLOPHANE**

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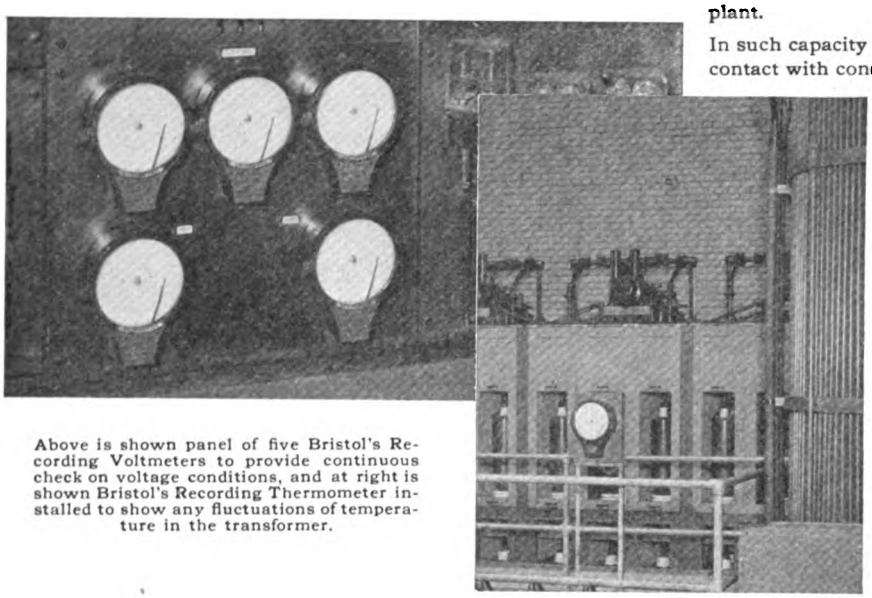
# Getting more efficient control of electrical power

The constantly increasing application of electrical power throughout industry opens an ever widening field for the practice of worthwhile power economy. Time and again it has been demonstrated that hundreds, and even thousands of dollars monthly, can be saved by instituting the "check-up with instruments" method of determining the operating efficiency of power generating equipment; and for conducting power surveys in the manufacturing plant.



Above is shown panel of five Bristol's Recording Voltmeters to provide continuous check on voltage conditions, and at right is shown Bristol's Recording Thermometer installed to show any fluctuations of temperature in the transformer.

In such capacity Bristol's Recording Instruments give an intimate contact with conditions which could be obtained in no other way —amount of current generated . . . voltages on distribution feeder lines . . . voltages maintained on incoming feeder lines to factories . . . and a hundred-and-one other current factors can be continuously recorded on the instrument charts. Moment-by-moment load fluctuations which may occur throughout the day and night are revealed, together with the exact time and extent of happening.

Such records permit the careful analysis of existing efficiencies, and enable those in charge of power maintenance to accurately apportion load in such a way as to bring about the most effective power consumption.

Simply and sturdily constructed, Bristol's Recording Instruments are inherently suited to continual plant use, and will perform satisfactorily for years with a minimum of care and adjustment.

*Detailed information in Catalog No. 1502.*

## The Bristol Company, Waterbury, Conn.

# IMPERVIOUS VARNISH COMPANY

*Manufacturers of*

**Insulating Varnishes, Coatings and Impregnating Gums**

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**ELECTRIC INDUSTRY—**

**Enamels, Japans, Protective Coatings and Varnishes**

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There is an "IMPERVIOUS VARNISH PRODUCT", Baking or Air-Drying, made for the ELECTRIC and AUTOMOBILE INDUSTRIES and for Manufacturers requiring an Enamel or Coating to obtain a finish of the highest grade and permanency.

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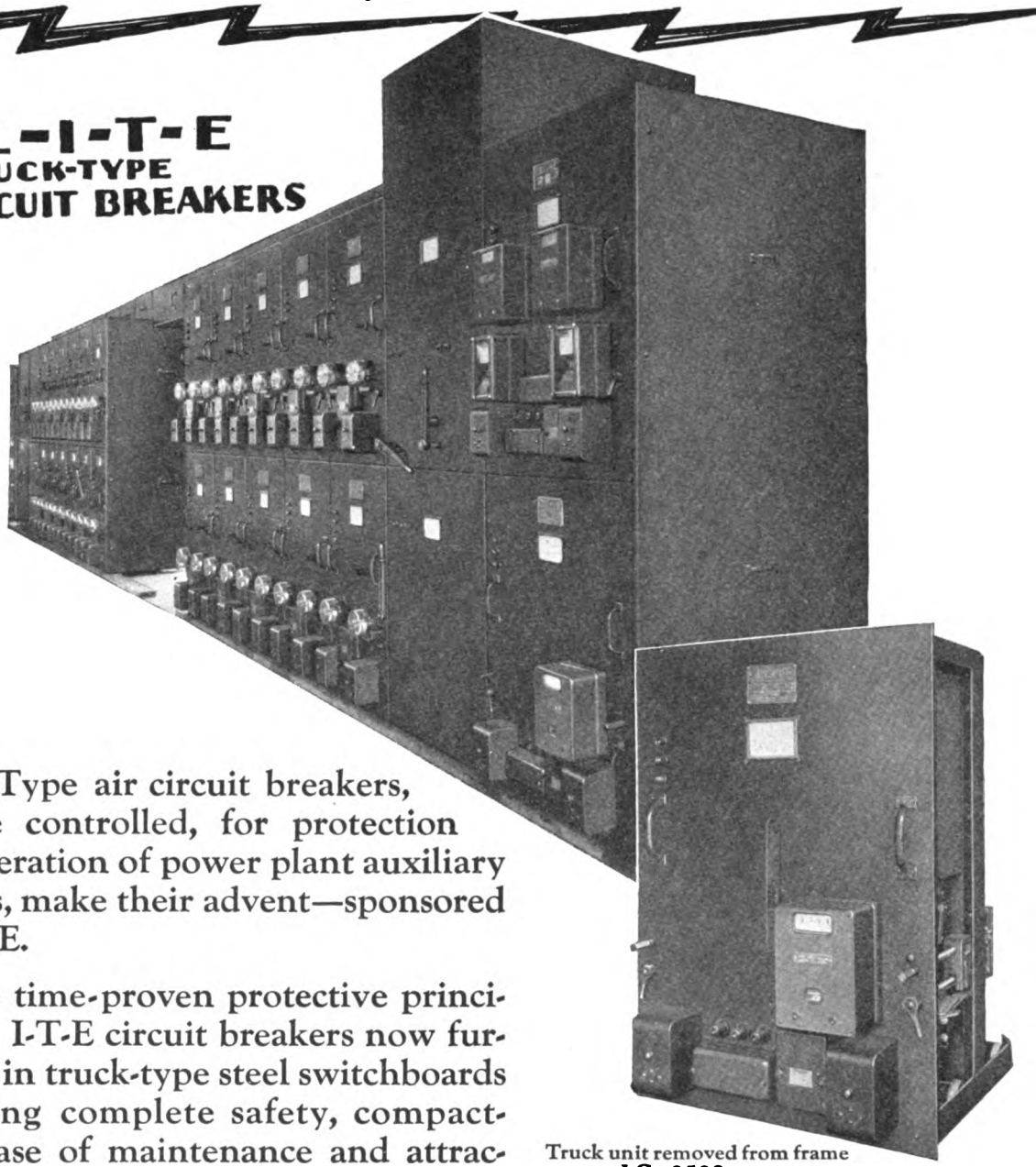
# Concentrated Control by I-T-E

## CEL-I-T-E TRUCK-TYPE AIR CIRCUIT BREAKERS



Truck-Type air circuit breakers, remote controlled, for protection and operation of power plant auxiliary circuits, make their advent—sponsored by I-T-E.

All the time-proven protective principles of I-T-E circuit breakers now furnished in truck-type steel switchboards affording complete safety, compactness, ease of maintenance and attractive appearance.

Truck unit removed from frame —type LG, 2500 amperes at 550 volts, 3 phase, 60 cycles.

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# I-T-E PROTECTION

## URELITES ~ ~ I-T-E CIRCUIT BREAKERS




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*Write for Samples stating requirements*

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HYDRO-PROOF TAPE
REGISTERED U.S. PATENT OFFICE

**Application**

Wrap the splice and forget it.

Eliminate painting with weather-proof compounds.

**Operation**

Permanent adhesion.

Splices can be opened for inspection and rewound with the same tape.

**Elkhart Rubber Works**
Elkhart - - - - Indiana




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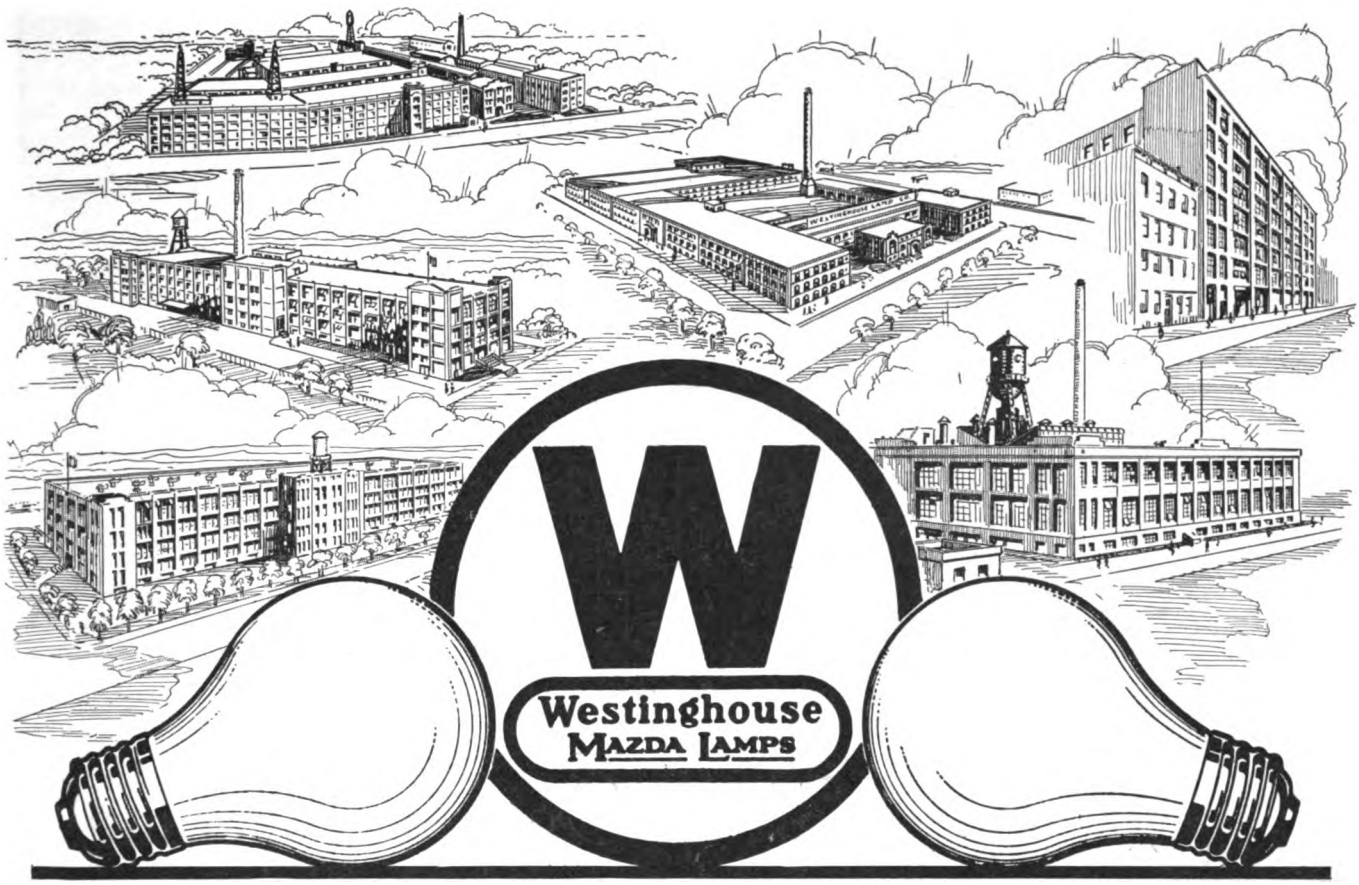


# Back of the Trade Mark

Of itself a trade mark means nothing.

It is the organization, principles and resources behind the trade mark which give it character and standing.

Back of the Westinghouse Lamp Company trade mark is a great personal organization in which each part works harmoniously with the other and in which each part is ready and willing to work with you.

The resources of the Westinghouse organization are inestimatable. The inventory shows factories, warehouses and equipment valued in the millions, but no reckoning can be made of the ingenuity, skill and character of the Westinghouse Illuminating Engineers who stand ready to assist in the solving of your lighting problems.

**Westinghouse Lamp Company**
**150 Broadway, New York, N. Y.**

# Westinghouse

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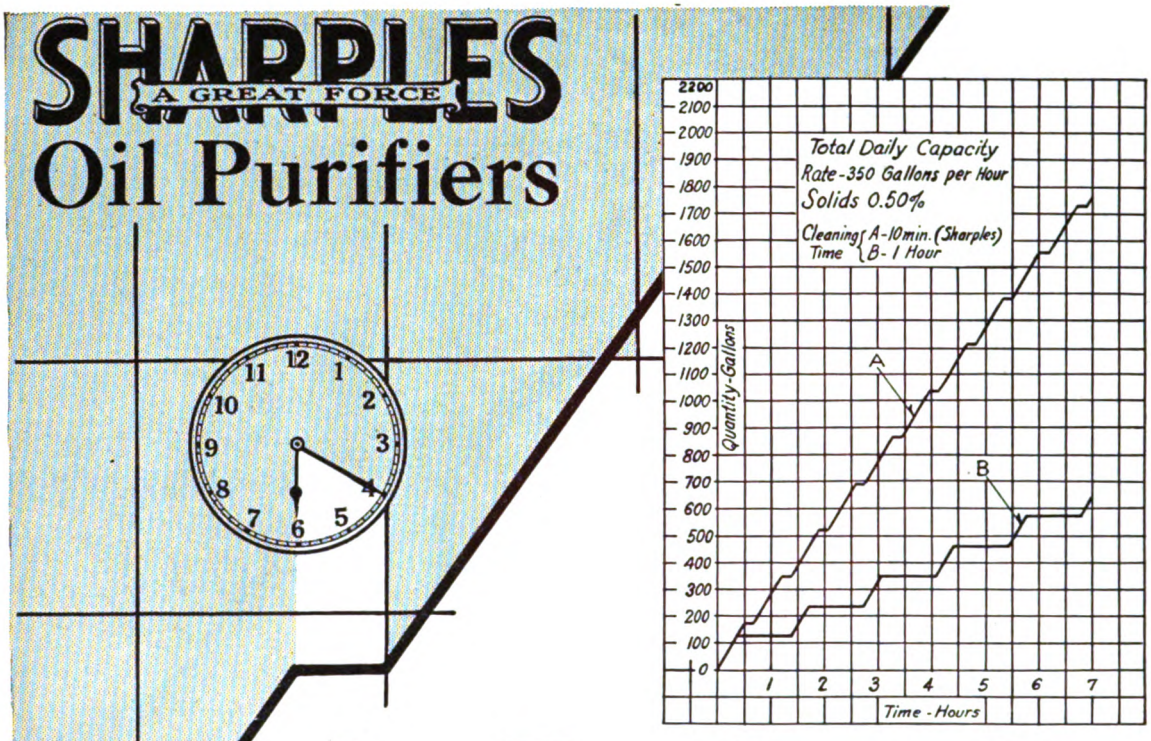
# SHARPLES
A GREAT FORCE
# Oil Purifiers

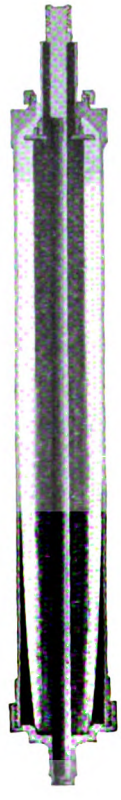



## Less Time-Out for Cleaning

## Increases All-day Capacity

THE SHARPLES BOWL

Used oil is fed in at the bottom. Sludge collects at the bottom, creeping up the side of the bowl. Oil and water separate as they travel up the bowl and are drawn off separately at the top. To clean the bowl, shut off the oil feed, stop the centrifuge, and drain.



TEN minutes time* removes the solid impurities from the Sharples Purifier. Thus the simplified Sharples bowl construction permits almost continuous useful operation--with very little time out for cleaning.

A graphic picture of a day's operation is given in the chart above. Notice how the Sharples production curve climbs steadily upward, reaching a creditable volume at the end of the day. Notice also in the other curve, how a complicated bowl necessitates much time out for cleaning and causes this curve to lag.

**In choosing your equipment for purifying transformer and circuit-breaker oil, remember the Sharples simplified bowl that can be cleaned in ten minutes --and develops a separating force 13000 times that of gravity.**

*Ten minutes includes the time necessary to stop the machine, clean the bowl, and return the machine to operating speed.

Westinghouse Electric & Manufacturing Company
East Pittsburgh Pennsylvania
Sales Offices in All Principal Cities of the United States and Foreign Countries

# Westinghouse

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## PERSONALS

Mr. James E. Davidson, vice-president and general manager of the Nebraska Power Co., Omaha, since 1917, has been elected president of the Company, succeeding Mr. W. H. Head who becomes chairman of the board. Mr. Davidson is well known to readers of the Journal through his activities in the National Electric Light Association of which he was president in 1925.

Mr. J. W. Young, formerly station design engineer for the Duquesne Light Co., Pittsburgh, Pa., has been appointed electrical engineer in charge of the newly formed engineering department of the Narragansett Electric Co., of Providence, Rhode Island.

Mr. George S. Humphrey, electrical engineer of the West Penn Power Co., Pittsburgh since 1918, has resigned to accept the position of chief engineer of the Potomac Edison Co. and subsidiary companies in charge of engineering and of the generation and transmission of power. Mr. Humphrey has been chairman of the Pittsburgh section of the A.I.E.E., and of the electrical section of the Engineers Society of Western Pennsylvania, of Pittsburgh.

Mr. Charles H. Kenney, distribution engineer of the Brooklyn Edison Co., has resigned to take up field engineering work in the metropolitan New York area with the Rome Wire Co. Division of General Cable Corporation.

Major D. W. Blakeslee has been promoted from the electrical and searchlight unit of the engineering and development branch to chief of administration branch, supply section, office of chief of engineers, Washington, D.C. Major Blakeslee is a former Westinghouse Engineer, having been for a number of years engaged in power engineering and industrial sales at the East Pittsburgh works.

Mr. Adam E. Daum, vice-president and treasurer of the Impervious Varnish Co. and president of the Pittsburgh Paint, Oil and Varnish Club, was elected a director of the National Paint, Oil and Varnish Association for three years at their recent annual convention in Detroit.

Mr. John N. Critchlow has been appointed general manager of sales of the Oliver Iron & Steel Co., Pittsburgh. He was formerly manager of the Company's Detroit office.

Mr. L. H. Waldrip, has been placed in charge of the new Cleveland office of the Driver-Harris Co. of Harrison, New Jersey, which is located at 7016 Euclid Avenue.

Mr. S. G. Rhodes, general superintendent of the distribution and installation department of The New York Edison Co., and consulting engineer of the United Electric Light & Power Co., died suddenly on November 22nd at his home. He had been with The New York Edison Co. since 1899.

## Westinghouse Club Notes

The Technical Sections of the Club have been better than ever this year both in attendance and quality of lectures. During the month of October, 93 sessions of the 18 Technical Sections were held with a total attendance of 4962 man-hours. During December there will be several outstanding lectures, among which are the following:—

December 3—"The Transportation Industry"—M. B. Lambert, Transportation Sales Manager.

December 3—"Competition in the Industrial Business"—Bernard Lester, Assistant Industrial Sales Manager.

December 4—"Supervisory Control and Remote Metering"—R. J. Wensley, Switchboard Engineering Dept.

December 4—"Personnel"—E. S. McClelland, Director of Personnel.

December 7—"Liquid Oxygen Demonstration and Movies"—J. A. Warfel, Air Products Sales Co.

December 12—"The Modern Cathode Ray Oscillograph"—R. Tanberg, Research Department.

On Thursday, December 13, the Club will hold its Annual Dinner at McCreerys. Reservations already made indicate an attendance of between eight and nine hundred. The principal speaker of the evening will be Mr. John L. Davis, humorist, philosopher and traveller. The public address system will be used so that all will be able to hear the speakers. Arrangements for this affair are being made by Major Charles H. Smith, President of the Club. Music will be furnished by the Club orchestra.

## NEW BOOKS

"Engineers"—1490 pages, 9 by 12 inches, numerous illustrations, Published by the Neo-Techni Research Corporation, General Motors Building, New York City. Price $15.00.

It is difficult in the space available to give a proper conception of a book of the magnitude of "Engineers". In the first place a great mass of engineering information is included in the five main sections of the book. These headings are devoted to civil engineering, electrical engineering, mechanical engineering, mining and metallurgical engineering, and fifth miscellaneous data including mathematical tables, safety engineering and data regarding various engineering and other societies. It is claimed that this publication is the result of five years of work by a large group of leading engineers. In addition to the technical pages, the feature of this book is the classified listing of the positions held and addresses of 220 600 engineers, representing 30 335 concerns in the United States and Canada. The offices of these companies. street addresses, branch managers and products are also included. The classification is geographic and in the electrical section is sub-divided under "Electrical Equipment" and "Public Utilities". The immense amount of work involved in such a directory can hardly be appreciated except by inspection of the book itself. Ownership of a copy certainly should be a valuable asset to anyone who has frequent occasion to want to know who's who in various organizations in different parts of the country. The book is printed on thin paper and handsomely bound in heavily embossed Fabrikoid.

The I-T-E Circuit Breaker Co., Philadelphia, Pa., have published their Bulletin No. 220 covering an entirely new type of protective equipment—the new U-RE-LITE all steel distribution groups. The safe enclosed units in the various arrangements illustrated are coming more and more into general use. Remote controlled units are also shown, built in accordance with experience gained under actual operating conditions at a number of utility operating companies. Copies of this Bulletin will be sent on request.

A new Industrial Lighting Booklet, No. 448-A, has been issued by the Holophane Company, Inc., 342 Madison Avenue, New York. This new edition lists many recent developments not mentioned in previous publications of the same character, a number of which have been developed for specific application in varied locations. The information contained in this booklet would be of value to industrial plants, industrial architects, electrical contractors, central stations, etc. Copies of the Booklet will be sent promptly on request.

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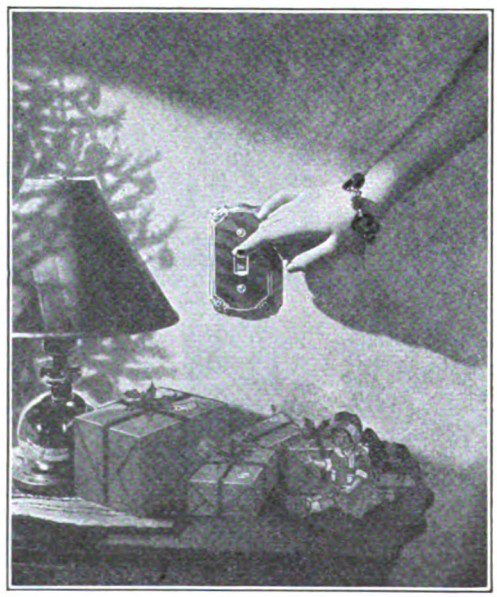

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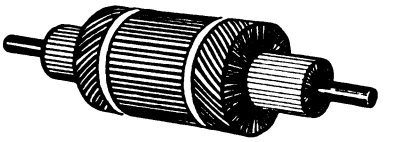

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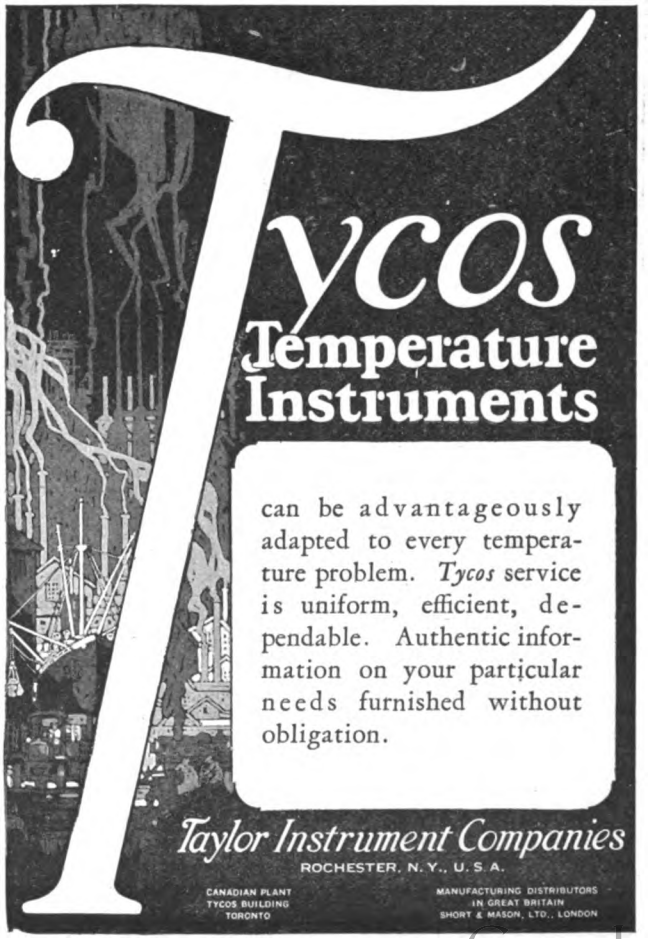
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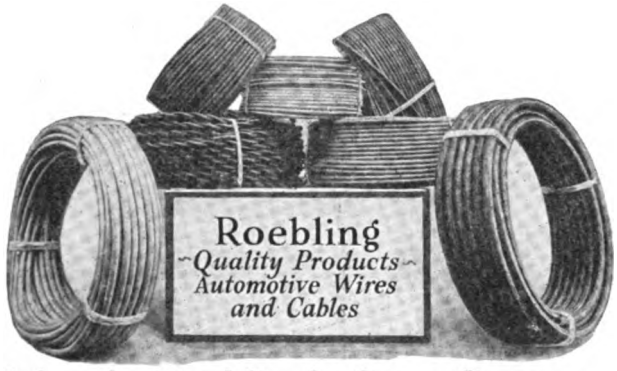


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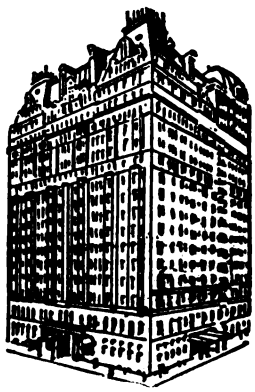

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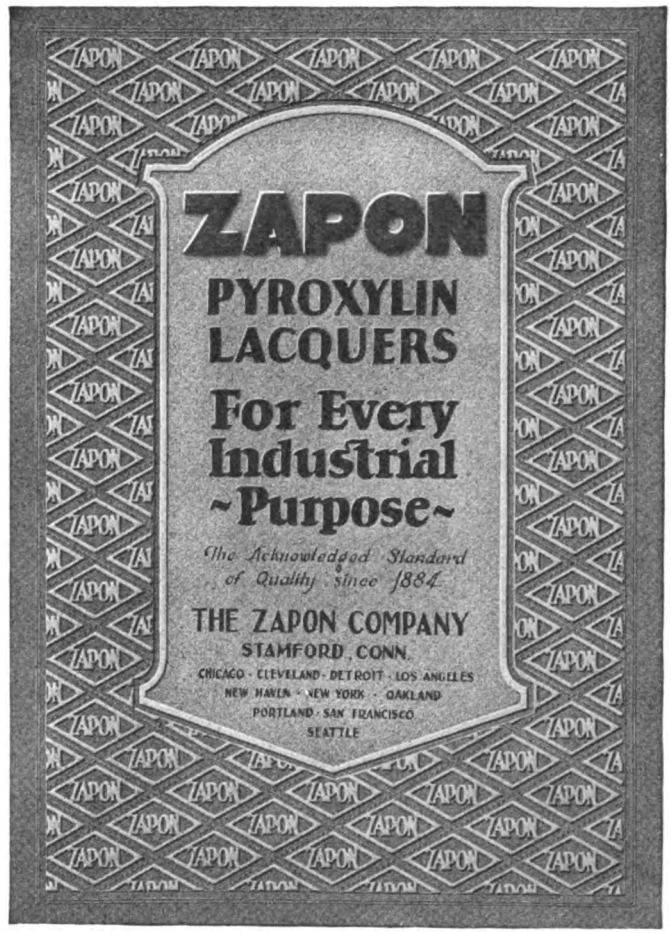




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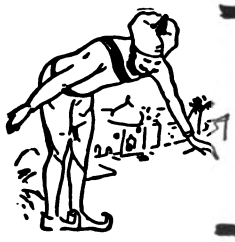

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American Brass Co. ..... 7
American Bridge Co. . .....
American Electrical Works . ..... 42
American Lead Pencil Co. .....
American Rolling Mills Co. .....
American Sheet & Tin Plate Co. ..... 20

**B**

Babcock & Wilcox Co., The..... 14
Bartlett-Haywood Co. . ..... 21
Bellevue-Stratford Hotel ..... 39
Benolite Co. . ..... 41
Blaw-Knox Co. ..... 24
Bond, M. & Co. . .....
Bristol Co., The ..... 30
Bryant Electric Co. ..... 36

**C**

Chalfonte Hotel . ..... 28
Clayton Mark Co. . .....
Crane Co. . ..... 17

**D**

Dexter & Sons, C. H. ..... 32
Driver-Harris Co. . .....
Diamond State Fibre Co. ..... 37

**E**

Electric Testing Laboratories ..... 32
Electrical Refractories Co. ..... 20
Elkhart Rubber Works . ..... 32

**F**

Fafnir Bearing Co. .....10, 11
Fuller Lehigh Co. ..... 3

**G**

Griscom-Russell Co., The..... 22

**H**

Hart Mfg. Co. ..... 23
Hazard Mfg. Co. ..... 25
Holbrook Rawhide Mfg. Co. ..... 28
Holophane Co. . ..... 29
Hoskins Mfg. Co. . ..... 42

**I**

Imperial Porcelain Works . ..... 38
Impervious Varnish Co. ..... 30
Ingersoll-Rand Co. . ..... 27
I-T-E Circuit Breaker Co. ..... 31

**J**

Jamestown Metal Desk Co. ..... 8
Jeandron, W. J. ..... 12

**L**

Link Belt Co. . ..... 9

**M**

Manning Paper Co. . ..... 40
Maring Wire Co. ..... 40
Martinque Hotel . . ..... 39
Moloney Electric Co. ..... 26
Morganite Brush Co. ..... 40
Morse Chain Co. ..... 12
McAlpin Hotel . ..... 14
McClellan & Junkerfield ..... 32
McGraw-Hill Book Co. .....

**N**

National Carbon Co. ..... 6
National Vulcanized Fibre Co. .....
New Departure Mfg. Co. ..... 44
Norma-Hoffman Bearing Co. ..... 13
Newport News Ship Building & Dry Dock Co. . ..... 22

**P**

Pelton Water Wheel Co., The..... 26
Pittsburgh Malleable Iron Co. ..... 18
Portland-Monson Slate Co. ..... 14
Public Service Production Co. ..... 32
Prack, H. B. ..... 32

**R**

Rawson Electrical Instrument Co. ..... 39
Rogers Paper Mfg. Co. ..... 40
Roebling Sons & Co., John A. ..... 38

**S**

Sargent & Lundy ..... 32
Schenectady Varnish Co. ..... 37
Sherwin-Williams Co. . ..... 40
Sharples Specialty Co. .....
Sipe & Co. ..... 42
Smith Co., S. Morgan .....
Smith & Dove Mfg. Co. ..... 36
South Bend Current Control Co..... 36
Speer Carbon Co. ..... 24
Stackpole Carbon Co. ..... 1
Standard Underground Cable Co. ..... 42
Star Porcelain Co. ..... 38
Sterling Varnish Co. . ..... 37
Stone & Webster ..... 4
Superheater Co. . ..... 38

**T**

Taylor Instrument Co. . ..... 37
Texas Co. . ..... 43
Timken-Roller Bearing Co. ..... 2

**U**

Union Electric Mfg. Co. ..... 38

**V**

Vacuum Oil Co. .....619
Vandervelde . . ..... 14

**W**

Walker Cotton Fabrics Co. ..... 18
Weller Mfg. Co. ..... 16
Westinghouse Electric & Mfg. Co..... 34
Westinghouse Lamp Co. . ..... 33
Westinghouse Traction Co. . ..... 19
West Virginia Pulp & Paper Co. ..... 18
Wheeler Wire Co. . ..... 36
White Eng. Corp., The, J. G..... 32
Wiley & Sons, John .....

**Z**

Zapon Co., The ..... 39



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# FIVE YEAR TOPICAL INDEX

OF

# THE ELECTRIC JOURNAL

WITH

## INDEX TO AUTHORS

FOR

VOL. XXI - - 1924
VOL. XXII - - 1925
VOL. XXIII - 1926
VOL. XXIV - 1927
VOL. XXV - 1928

PUBLISHED BY
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# OUTLINE KEY TO TOPICAL INDEX

## VOLUMES XXI, XXII, XXIII, XXIV and XXV

THIS Index, as well as the previous indexes, is arranged according to the topical classification of subjects. The original scheme for this method of indexing was published in the Journal for February, 1906. All articles which have appeared in the Journal since its initial issue can be located quickly by the use of the Ten-Year Index, (1904-1913), the Five-Year Index (1914-1918), the Five Year Index (1919-1923), and the present Five Year Index, which covers 1924, 1925, 1926, 1927 and 1928.

Abbreviations: (*E*)—Editorial; *T*—Number of Tables; *C*—Number of Curves; *D*—Number of Diagrams; *I*—Number of Illustrations; *W*—Number of Words; *QB*—Question Box; *ROD*—Railway Operating Data. (The numerals following *ROD* are volume and page numbers.) The main headings and sub-divisions are as follows:—

## MECHANICAL ENGINEERING


GENERAL . . . . . 3 BRAKES . . . . . 3 STEAM . . . . . 3


## ELECTRICAL ENGINEERING

### GENERAL


STANDARDS—MATERIALS—Insulation . 4
MEASUREMENTS—METERS—RELAYS . . 4
THEORY . . . . . 5


### GENERATION


POWER PLANTS—Substations . . . . . 6
DYNAMOS AND MOTORS—Armatures—Bearings — Commutators — Field Windings . . . . . 6
DIRECT CURRENT—Shunt and Compound—Series—Commutating Pole . 7
ALTERNATING CURRENT—Alternators—Synchronous Motors—Induction Motors—Fan Motors . . . . . 8


### TRANSFORMATION


RECTIFIERS . . . . . 9
SYNCHRONOUS CONVERTERS . . . . . 9
STORAGE BATTERIES . . . . . 9
TRANSFORMERS—Connections — Performance — Testing—Instrument—Autotransformers—Reactance Coils 10
CONDENSERS . . . . . 11


### TRANSMISSION, CONDUCTORS AND CONTROL


GENERAL—Power-Factor — Systems—Phasing . . . . . 11
LINES — Overhead — Underground—Conductors . . . . . 12
SWITCHBOARDS—Interrupting Devices—Protective . . . . . 12
REGULATION AND CONTROL—Regulators—Controllers—Rheostats . . . . . 13


### UTILIZATION


GENERAL—Electrochemistry . . . . . 14
LIGHTING . . . . . 14
POWER—Motors and Applications—Heating Apparatus—Welding—Magnets . . . . . 14
INTELLIGENCE TRANSMISSION . . . . . 15


## RAILWAY ENGINEERING


GENERAL . . . . . 16 MOTIVE POWER — Locomotives —Cars —Maintenance and Repairs . . . . . 16 MINING . . . . . 17


## MISCELLANEOUS


GENERAL—Works Management . . . . . 17
ENGINEERING SOCIETIES . . . . . 17
THE ENGINEER—Education—Personal —Pantent Law . . . . . 17
THE JOURNAL . . . . . 18


## INDEX TO AUTHORS


(pp. 19-26)


## THE JOURNAL QUESTION BOX

References in the Index to The Journal Question Box are given by numbers. The questions and answers during 1924, 1925, 1926, 1927 and 1928 appeared as follows:

| | 1924 | 1925 | 1926 | 1927 | 1928 |
|---|---|---|---|---|---|
| January | 2313-2335 | 2445-2452 | 2577-2581 | 2689-2704 | 2785-2801 |
| February | 2336-2350 | 2453-2462 | 2582-2584 | 2705-2708 | 2802-2804 |
| March | 2351-2356 | 2463-2483 | 2585-2599 | 2709-2717 | 2805-2813 |
| April | 2357-2369 | 2484-2487 | 2600-2607 | 2718-2728 | 2814-2825 |
| May | 2370-2371 | 2488-2496 | 2608-2615 | 2729-2731 | 2826-2829 |
| June | 2372-2373 | 2497-2501 | 2616-2623 | 2732-2738 | 2830-2837 |
| July | 2374-2387 | 2502-2511 | 2624-2627 | 2739-2743 | 2838-2844 |
| August | 2388-2396 | 2512-2515 | 2628-2642 | 2744-2751 | 2845-2849 |
| September | 2397-2421 | 2516-2534 | 2643-2663 | 2752-2760 | 2850-2864 |
| October | 2422-2432 | 2535-2543 | 2664-2674 | 2761-2772 | 2865-2872 |
| November | 2433-2439 | 2544-2549 | 2675-2677 | 2773-2775 | 2873-2876 |
| December | 2440-2444 | 2550-2576 | 2678-2688 | 2776-2784 | 2877-2883 |


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# MECHANICAL ENGINEERING

## GENERAL

**Balancing Large Rotating Apparatus**—L. C. Fletcher. D-2, I-3, W-3950. Vol. XXI, p. 5, Jan., '24.

**The Dynamic Balance of Small High-Speed Armatures**—Wm. E. Trumpler. C-1, I-8, W-5450. Vol. XXII, p. 34, Jan., '25.

**Field Balancing of Rotors**—James J. Ryan. T-2, D-9, I-1, W-6600. Vol. XXV, p. 596, Dec., '28.
(E) Chas. R. Riker. W-450. p. 574.

**The Vibration Problem in Engineering**—C. R. Soderberg. T-3, C-17, D-11, I-34, W-33500. Vol. XXI, p. 39, Jan., '24; p. 53, Feb., '24; p. 89, Mar., '24; p. 160, Apr., '24; p. 295, June, '24; p. 330, July, '24; p. 579, Dec., '24; Vol. XXIII, p. 71, Feb., '26.

**The Problem of Vibration**—G. M. Eaton. (E) W-300. Vol. XXI, p. 4, Jan., '24.

**Vibration Absorbers in Large Single-Phase Machines**—C. R. Soderberg. C-2, D-2, I-5, W-2980. Vol. XXI, p. 383, Aug., '24.

**Accelerometers**—F. Paulsen. I-12, W-1700. Vol. XXIII, p. 475, Sept., '26.

**What's New in Prime Movers**—Alex D. Bailey. (E) W-500. Vol. XXIV, p. 243, June, '27.

**A Four Crane Team**—W-350. Vol. XXV, p. 414, Aug., '28.

**Failure of Coupling Bolts**—QB, 2410.

**Rate of Water Flow in Tunnels**—QB, 2796.

## GEARS

Gears and Pinions—ROD, XXIII, p. 89.

**Railway Motor Gearing**—ROD, XXIII, p. 142.

**Gear Center Distances on Railway Motors**—ROD, XXV, p. 315.

## BRAKES

**Magnetic Brakes and Their Application**—D. W. Dean. T-1, I-6, W-2400. Vol. XXIV, p. 329, July, '27.

**Dynamic Braking with Different Types of Motors**—QB, 2769.

## STEAM

**The Passing of the Reciprocating Engine**—S. S. Wales (E) W-350. Vol. XXIII, p. 272, June, '26.

**High-Pressure Steam; Its Advantages and Disadvantages**—Harold Anderson. T-2, C-1, W-3200. Vol. XXIV, p. 426, Sept., '27.

**Air Ejectors for Industrial Applications**—J. W. McNulty. C-1, I-4, W-1000. Vol. XXIV, p. 505, Oct., '27.

## Turbines

**Steam Turbines and Condensing Equipment**—Francis Hodgkinson. T-2, C-9, I-18, W-12 350. Vol. XXI, p. 505, Nov., '24; p. 548, Dec., '24.
(E) E. H. Sniffin. W-350, p. 497.

**The Design and Manufacture of Blading for Steam Turbines—The Methods Used at the South Philadelphia Works**—L. L. Smith. I-29, W-3740. Vol. XXII, p. 202, May, '25.

**The Floating Type of House Turbine**—Ralph Kelly. D-1, I-2, W-1750. Vol. XXII, p. 299, June, '25.

**Some Problems in Connection with the Design of Large Turbines**—Warren B. Flanders. I-7, W-6000. Vol. XXIII, p. 213, May, '26.

**The Field and Limitations of Extraction Turbines**—C. B. Campbell. C-2, W-3400. Vol. XXIV, p. 553, Nov., '27.

**Building Large Steam Turbine Spindles**—J. P. Rigsby. I-7, W-3500. Vol. XXIV, p. 591, Dec. '27.

**New 40 000 Kilowatt Turbines for the Duquesne Light Company**—J. D. Schmidt. I-5, W-1850. Vol. XXV, p. 36, Jan., '28.

**165 000 Kw. Turbine Generator for Hell Gate**—H. J. Hanzlik. I-5, W-3150. Vol. XXV, p. 274, June, '28.

**Unusual Vibration of a 25 000 Kw Turbine**—Thomas C. Rathbone. C-10, I-3, W-5000. Vol. XXV, p. 88, Feb., '28.

**Recent Developments in Steam Turbine Cylinder Joint Fastenings**—J. B. Walbridge. I-2, W-1300. Vol. XXV, p. 197, Apr., '28.

**The Development of Public Utility Prime Movers**—A. D. Hunt. (E) W-450. Vol. XXV, p. 266, June, '28.

**Making the Small Turbine Safe**—C. L. Southmayd. I-4, W-1850. Vol. XXV, p. 514, Oct., '28.

**Recent Developments in the Design of Impulse-Reaction Steam Turbines**—R. C. Allen. I-2, W-2900. Vol. XXV, p. 534, Nov., '28.

**Running Reaction Turbine without Water**—QB, 2646.

**Operation of Bleeder-Turbine Driven Generator**—QB, 2875.

## Governors

**Fluid Governors for Prime Movers**—Henry F. Schmidt. Vol. XXV.

**I—Historical.** I-9, W-2000. p. 168, Apr., '28.
(E) A. D. Hunt. W-350. p. 167.

**II—Type Characteristics.** C-1, I-9, W-3300. p. 238, May, '28.

**III and IV—Operating Mechanism.** I-19, W-6100. p. 303, June; p. 354, July, '28.

**V—Governing Impellers.** I-7, W-2200. p. 406, Aug., '28.

**VI—Remote Control.** T-2, I-10, W-4550. p. 451, Sept., '28.

## Condensers

**The Steam-Jet Condensing-Type Vacuum Pump**—J. H. Smith. C-5, I-6, W-4950. Vol. XXII, p. 17, Jan., '25.

**Factors which Influence the Performance of a Steam Surface Condenser**—U. A. Taddiken. C-2, I-1, W-950. Vol. XXV, p. 160, Mar., '28.

**Air Ejector Selection for Surface Condenser Installations**—C. B. Tuley. (E) W-650. Vol. XXV, p. 573, Dec., '28.

**Trouble In Condenser Air Pump**—QB, 2478.

# ELECTRICAL ENGINEERING

## GENERAL

**Superpower From the Human Standpoint**—W. S. Rugg. (E) W-1450. Vol. XXI, p. 1, Jan., '24.

**Design Research**—Chas. R. Riker. (E) W-1300. Vol. XXI, p. 87, Mar., '24.

**A World Power Survey**—A. H. McIntire. (E) W-440. Vol. XXI, p. 87, Mar., '24.

**Public Relations**—H. T. Sands. (E) W-270. Vol. XXI, p. 191, May, '24.

**"Superpower" and the Farmer**—R. F. Pack. (E) W-230. Vol. XXI, p. 192, May, '24.

**Our "Far Eastern" Neighbors to the West**—Gen. Guy E. Tripp. (E) W-250. Vol. XXI, p. 194, May, '24.

**Facing the Facts Regarding Rural Service**—C. S. Cook. (E) W-450. Vol. XXI, p. 196, May, '24.

**The Beginning of Superpower**—Chas. F. Scott. (E) W-450. Vol. XXI, p. 200, May, '24.

**The First World Power Conference**—C. E. Skinner. (E) W-250. Vol. XXI, p. 402, Sept., '24.

**Influence of Radio on Power Development**—Chas. R. Riker. (E) W-1300. Vol. XXII, p. 52, Feb., '25.

**Facts to Drive Out Misconceptions**—M. S. Sloan. (E) W-1700. Vol. XXII, p. 149, Apr., '25.

**"— and a Little Child Shall Lead Them"**—J. E. Davidson. (E) W-950. Vol. XXII, p. 243, June, '25.

**Eternal Vigilance**—Robert F. Pack. (E) W-950. Vol. XXII, p. 244, June, '25.

**The Wider Scope of Our Service Obligation**—H. T. Sands. (E) W-550. Vol. XXII, p. 245, June, '25.

**Public Utilities as Community Builders**—P. S. Arkwright. (E) W-500. Vol. XXII, p. 245, June, '25.

**Why Electricity Is Cheap**—Wigginton E. Creed. (E) W-500. Vol. XXII, p. 248, June, '25.

**Electric Light and Power Investment Companies**—Martin J. Insull. (E) W-1500. Vol. XXII, p. 249, June, '25.

**When Customers are Partners**—A. Emory Wishon. (E) W-1300. Vol. XXII, p. 250, June, '25.

**Electric Service On the Pacific Coast**—Frank A. Leach, Jr. (E) W-1050. Vol. XXII, p. 252, June, '25.

**Managerial Burden in Large Enterprises**—Edwin D. Dreyfus. (E) W-1050. Vol. XXII, p. 253, June, '25.

**National Electric Service**—G. E. Tripp. W-2640. Vol. XXII, p. 255, June, '25.

**Management-Investment Companies Mean Greater and Cheaper Service to the Public**—John J. O'Brien. (E) W-650. Vol. XXII, p. 254, June, '25.

**Then and Now**—Chas. R. Riker. (E) W-2050. Vol. XXIII, p. 1, Jan., '26.

**Simplicity and Success**—Charles R. Underhill. (E) W-350. Vol. XXIII, p. 51, Feb., '26.

**The Privilege of Public Service**—M. S. Sloan. (E) W-750. Vol. XXIII, p. 93, Mar., '26.

**Cost of Electric Service a Small Percentage of Total Expense**—R. F. Pack. (E) W-1850. Vol. XXIII, p. 202, May, '26.

**Maintain Progressiveness in the Future**—P. S. Arkwright. (E) W-800. Vol. XXIII, p. 204, May, '26.

**Why We Have Split Our Stock**—John B. Miller (E) W-750. Vol. XXIII, p. 205, May, '26.

**Water Power Development**—W. E. Creed. (E) W-600. Vol. XXIII, p. 205, May, '26.

**Electric Service in New Jersey**—T. N. McCarter. (E) W-1900. Vol. XXIII, p. 209, May, '26.

**The Nation's Power Metropolis**—J. M. Graves. (E) W-1500. Vol. XXIII, p. 210, May, '26.

**Vital Electric Statistics**—A. H. McIntire. (E) W-550. Vol. XXIII, v. 212, May, '26.

**The Removal of Limitations**—H. W. Smith. (E) W-500. Vol. XXIII, p. 338, July, '26.

**So Trim Your Sales**—J. M. Hipple. (E) W-850. Vol. XXIII, p. 441, Sept., '26.

**The Field of the Engineer**—W. S. Rugg. (E) W-1800. Vol. XXIII, p. 589, Dec., '26.

**Electrical Developments in 1926**—H. W. Cope. (E) W-2700. Vol. XXIV, p. 1, Jan. '27.

**Our Mechanical Slaves**—Chas. R. Riker, (E) W-1200. Vol. XXIV, p. 53, Feb., '27.

**The Control's the Thing**—Chas. R. Riker. (E) W-900. Vol. XXIV, p. 193, May, '27.

**Let's Make It Our Business to Sell Electric Energy**—R. F. Pack. (E) I-1, W-700. Vol. XXIV, p. 235, June, '27.

**American Initiative and American Cooperation**—H. T. Sands. (E) W-600. Vol. XXIV, p. 236, June, '27.

**We are Still Pioneers in Electric Service**—P. S. Arkwright. (E) W-400. Vol. XXIV, p. 236, June, '27.

**Why is Our Industry Suffering from an Inferiority Complex?**—John B. Miller. (E) W-400. Vol. XXIV, p. 237, June, '27.

**Let's Make America Thrill with Pride of the Electrical Industry**—M. S. Sloan. (E) W-800. Vol. XXIV, p. 237, June, '27.

**Making Opportunities for More Engineering**—J. E. Davidson. (E) W-600. Vol. XXIV, p. 238, June, '27.

**The Growth of the Electrical Industry**—An Expression of Individualism—Paul S. Clapp. (E) W-1300. Vol. XXIV, p. 239, June, '27.

**The Development of Our Electric Service**—E. M. Herr. (E) W-600. Vol. XXIV, p. 241, June, '27.

**Economic Laws Apply to Water Power Development**—Wigginton E. Creed. (E) W-400. Vol. XXIV, p. 243, June, '27.

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**Increasing Co-operation in Inductive Coordination Work**—J. C. Martin. (E) W-600. Vol. XXIV, p. 244, June, '27.

**The Importance of Holding Companies to Small Cities, Towns and Farms**—John J. O'Brien. (E) W-400. Vol. XXIV, p. 244, June, '27.

**Good Engineering in Power Generation and Distribution**—H. R. Woodrow. (E) W-900. Vol. XXIV, p. 245, June, '27.

**Hydro-Electric Developments and Tendencies**—H. L. Doolittle. (E) W-600. Vol. XXIV, p. 247, June, '27.

**Central Station Power**—Samuel S. Wales. (E) I-1, W-1000. Vol. XXIV, p. 307, July, '27.

**Power Development**—C. S. Proudfoot. (E) W-1000. Vol. XXIV, p. 309, July, '27.

**Electrification of Industry Means Increased Profits**—Brent Wiley. (E) W-1200. Vol. XXIV, p. 310, July, '27.

**Conservation in Relation to Mental Limitations**—A. H. McIntire. (E) W-900. Vol. XXIV, p. 578, Dec., '27.

**Financing Public Utilities**—Theodore F. Smith. W-4600. Vol. XXIV, p. 596, Dec., '27.

**Present Trends of Central Station Development**—E. C. Stone. (E) W-400. Vol. XXV, p. 1, Jan., '28.

**Nineteen Twenty-Seven and Electrical Progress**—H. W. Cope. (E) W-4800. Vol. XXV, p. 1, Jan., '28.

**Japan from an Electrical Engineer's Viewpoint**—W. L. Newmeyer. I-7, W-3450. Vol. XXV, p. 6, Jan., '28.

**A Persistent Fallacy**—Roger L. Knight. (E) W-400. Vol. XXV, p. 58, Feb., '28.

**It's the Limit**—Chas. R. Riker. (E) W-550. Vol. XXV, p. 58, Feb., '28.

**Changes in Design Practice**—H. D. James. (E) W-450. Vol. XXV, p. 167, Apr., '28.

**Centrifugal Force—A Demon Enslaved**—Chas. R. Riker. (E) W-200. Vol. XXV, p. 208, May, '28.

**Strive for Higher Standards of Public Service**—H. T. Sands. (E) I-1, W-600. Vol. XXV, p. 255, June, '28.

**The Job of the Electrical Industry**—P. S. Arkwright. (E) W-750. Vol. XXV, p. 256, June, '28.

**The Intangible Interconnection between Utilities**—John B. Miller. (E) W-450. Vol. XXV, p. 256, June, '28.

**The Electrification of America**—M. S. Sloan. (E) W-750. Vol. XXV, p. 257, June, '28.

**Politics, Propaganda and Public Service**—W. Alton Jones. (E) W-350. Vol. XXV, p. 258, June, '28.

**Electricity—the Great Civilizer**—E. M. Herr. (E) W-1100. Vol. XXV, p. 258, June, '28.

**The Engineer Has a Sales Objective**—C. Ernest Greenwood. (E) W-450. Vol. XXV, p. 259, June, '28.

**We Must Keep Up With the Procession**—Major H. S. Bennion. (E) W-600. Vol. XXV, p. 260, June, '28.

**Should Our Water Power Resources Be Developed**—Paul A. Schoellkopf. (E) W-950. Vol. XXV, p. 262, June, '28.

**Electric Industry Faces the Task of Commercial Development**—John J. O'Brien. (E) W-450. Vol. XXV, p. 263, June, '28.

**Economic and Governmental Regulation Inseparably Mixed**—Edwin D. Dreyfus. (E) W-500. Vol. XXV, p. 264, June, '28.

**Friendship in Engineering and Business**—A. J. Standing. (E) I-1, W-950. Vol. XXV, p. 319, July, '28.

**Progress and Success of Electrical Engineering**—C. S. Proudfoot. (E) W-700. Vol. XXV, p. 320, July, '28.

**The Lure of the Difficult**—Leon R. Ludwig. (E) W-500. Vol. XXV, p. 421, Sept., '28.

**Relations between Central Station Engineers and Prime Mover Manufacturers**—G. H. Cox. (E) W-500. Vol. XXV, p. 528, Nov., '28.

## STANDARDS

**Simplified Practice**—Paul MacGahan. (E) W-860. Vol. XXI, p. 303, July, '24.

**A New Edition of A. I. E. E. Standards**—F. D. Newbury. W-4800. Vol. XXII, p. 447, Sept., '25.

(E) C. E. Skinner. W-450, p. 412.

**Standardization and Progress**—E. C. Stone. (E) W-900. Vol. XXIII, p. 208, May, '26.

**International Standards**—(E) W-550. Vol. XXIII, p. 393, Aug., '26.

**The Future of the Standardization Movement**—(E) W-900. Vol. XXIV, p. 145, Apr., '27.

**International Electrical Standardization**—C. E. Skinner. (E) W-900. Vol. XXIV, p. 577, Dec., '27.

**Standardization of Electrical Measuring Instruments**—Paul MacGahan. (E) W-750. Vol. XXV, p. 573, Dec., '28.

**Something New in Standards**—W. S. Rugg. (E) W-650. Vol. XXV, p. 265, June, '28.

**Heater Cord Standards**—Frank Thornton, Jr. (E) W-500. Vol. XXV, p. 265, June, '28.

## MATERIALS

**The Application of Materials in Design**—T. D. Lynch. (E) W-1100. Vol. XXIII, p. 93, Mar., '26.

**The Magnetic Properties of Silicon Steel in a Large Transformer**—G. H. Cole. C-42, D-1, W-4440. Vol. XXI, p. 17, Jan., '24.

**Effect of Punching Strains on the Magnetic Properties of Electrical Sheet Steel**—G. H. Cole. T-7, C-12, I-4, W-3850. Vol. XXI, p. 55, Feb., '24.

**The Properties and Testing of Magnetic Materials**—T. Spooner. Vol. XXII.

**I—Characteristics of Magnetization and Permeability Curves.** T-2, C-6, W-3100. p. 78, Feb., '25.

**II—Normal Hysteresis and Eddy Currents.** T-1, C-6, W-2900. p. 132, Mar., '25.

**III—Range of Permeability and Core-Loss Values.** C-15, W-4030. p. 180, Apr., '25.

**IV—Range of Permeability and Core-Loss Values.** C-13, W-2980. p. 230, May, '25.

**V—Permanent Magnet Steels.** T-1, C-8, W-6100. p. 394, Aug., '25.

**VI—Hysteresis Under Special Conditions.** C-13, W-3080. p. 441, Sept., '25.

**VII—Effect of Frequency On Permeability and Losses.** T-2, C-9, I-1, W-5000. p. 508, Oct., '25.

**VIII—Effects of Direction of Grain and Mechanical Stress On Magnetic Properties.** T-2, C-8, I-1, W-3550. p. 554, Nov., '25.

**IX—Effect of Heat Treatment.** C-14, W-5250. p. 610, Dec., '25. Vol. XXIII

**X—Effect of Heat Treatment.** T-2, C-15, W-3360. p. 24, Jan., '26.

**XI—Effect of Temperature.** T-2, C-14, W-2760. p. 79, Feb., '26.

**XII—Alternating Magnetizing Current and Mechanical and Thermal Properties of Electrical Sheet.** T-3, C-11, W-1860. p. 106, Mar., '26.

**Magnetic Analysis**—T. Spooner. C-12, D-2, I-1, W-5000. Vol. XXII, p. 118, Mar., '25.

(E) Chas. R. Riker. W-900, p. 101.

**A New Resistor for Use in Measurements of Impulse Voltages and Currents**—Edward Beck. I-5, W-900. Vol. XXV, p. 157 Mar. '28.

**Bimetal: The Temperature Sentinel**—H. E. Cobb. I-8, W-2750. Vol. XXV, p. 288, June, '28.

**The Development of a New, High-Temperature Solder**—Dr. James Silberstein. T-3, I-5, W-2600. Vol. XXV, p. 543, Nov., '28.

**Solder for Railway Electrical Work**—ROD, XXIV, p. 46.

**Mica and Its Application to Railway Equipment**—ROD, XXIV, p. 575.

**Preventing Oxidation of Cast Iron at High Temperatures**—QB, 2502.

**Oxidation-Resisting Thin Sheet Metals**—QB, 2526.

**Permalloy for Field Pole Cores**—QB, 2704.

**Core Loss Curves of Sheet Steel**—QB, 2736.

**Aluminum and Copper Coils**—QB, 2754.

**An Unusual Case of Magnetism**—QB, 2854.

## Insulation

**Dielectric Absorption in Fibrous Insulating Materials**—R. E. Marbury and E. R. Le Ghait. C-11, D-3, I-11, W-10 900. Vol. XXII, p. 526, Nov.; p. 605, Dec., '25.

**The Manufacture of Built-Up Mica**—J. R. McClain. T-1, C-1, I-4, W-5450. Vol. XXI, p. 10, Jan., '24.

**Insulating Oils for Oil Circuit Breakers**—Dean Harvey. C-1, I-6, W-4900. Vol. XXI, p. 573, Dec., '24.

**Testing Insulation with High Frequency**—J. L. Rylander. I-11, W-2050. Vol. XXV, p. 10, Jan., '28.

**A New Type of Turbogenerator Rotor Insulation**—M. D. Ross. I-6, W-1350. Vol. XXV, p. 63, Feb., '28.

**Electrical Insulating Oil**—Dean Harvey. C-1, I-11, W-5800. Vol. XXV, p. 96, Feb.; p. 127, Mar., '28.

**Effects of Corona in Various Gases on Insulation and Losses**—C. F. Hill. C-1, I-2, W-550. Vol. XXV, p. 402, Aug., '28.

**Dielectric Losses in Oil Impregnated Paper**—E. R. LeGhait. C-13, D-3, W-5150. Vol. XXV, p. 187, Apr., '28.

**Methods of Lapping Tape**—A. C. Roe. T-2, I-10, W-1450. Vol. XXV, p. 365, July, '28.

**Treated Fabric and Treated Fabric Tapes.** W-750. Vol. XXV, p. 569, Nov., '28.

**Testing Insulating Varnishes**—ROD, XXI, p. 394.

**Insulating a Railway Motor Armature**—ROD, XXI, p. 585.

Testing Mica—QB, 2349.

**Use of Varnished Cambric for Taping High-Voltage Conductors**—QB, 2452.

**Heat-Resisting Insulating Material**—QB, 2519.

**Magnet Wire Insulation**—QB, 2599.

**Motor Insulation Test**—QB, 2783.

### INSULATORS

**A Suspension Insulator for High-Voltage Systems**—D. F. Miner. C-1, I-14, W-1850. Vol. XXI, p. 560, Dec., '24.

**The Application of High-Tension Insulators**—T. B. Fleming. T-1, C-2, W-1580. Vol. XXI, p. 217, May, '24.

**Selection of Porcelain for Electrical Purposes**—H. M. Kraner. T-1, C-1, I-13, W-2660. Vol. XXIII, p. 344, July, '26.

(E) David R. Kellogg. W-850, p. 337.

**Field Test for Condenser Type Bushing**—QB, 2846.

**Bonding Insulator Pins on High-Tension Lines**—QB, 2377.

**Corrosion of High-Voltage Copper Conductor at Bushings**—QB, 2625.

## MEASUREMENT

**The Totalization of Power Readings**—R. T. Pierce. D-4, I-3, W-1300. Vol. XXI, p. 103, Mar., '24.

**Commercial Methods of Carbon Resistance Measurement**—Roscoe Wilmeth. T-1, D-5, I-3. Vol. XXI, p. 309, July, '24.

**The Value of Commercial Magnetic Testing**—T. Spooner. C-3, W-2980. Vol. XXI, p. 374, Aug., '24.

**A High-Tension Bridge for Measurement of Dielectric Losses In Cables**—R. W. Atkinson. D-6, I-1, W-7780. Vol. XXII, p. 58, Feb., '25.

(E) Donald M. Simons. W-450, p. 51.

**A Six-Element Portable Oscillograph Made Possible By a New Form of Permanent Magnet**—J. W. Legg. C-1, D-1, I-6, W-2400. Vol. XXII, p. 108, Mar., '25.

**The Klydonograph—A Practical Surge Recorder**—J. H. Cox. C-1, D-1, I-15, W-2830. Vol. XXIV, p. 5, Jan., '27.

**Switching-Surge Investigations with the Klydonograph**—P. H. McAuley. T-5, D-1, I-2, W-2340. Vol. XXIV, p. 9, Jan., '27.

**The Thermoradiometer and Some Examples of Its Application**—Professor Matsujiro Oyama. C-6, I-8, W-2580. Vol. XXIV, p. 26, Jan., '27.

**An Instrument for Progress**—Chas. R. Riker. (E) W-900. Vol. XXIV, p. 363, Aug., '27.

**Technique of Dufour Cathode-Ray Oscillograph for the Study of Short-Time Phenomena**—G. F. Harrington and A. M. Opsahl. D-6, I-12, W-2600. Vol. XXIV, p. 384, Aug., '27.

**Oscillography**—Joseph W. Legg. Vols. XXIV and XXV.

**I—Types of Oscillographs, Illuminants and Optical Systems.** I-6, W-5100. p. 268, June, '27.

**II—The Osiso in Its Various Forms.** D-5, I-10, W-4000. p. 341, July, '27.

**III—The Osiso as a Phonoscope for the Deaf.** T-1, D-6, I-3, W-5600. p. 398, Aug., '27.

**IV—The Osiso Exhibitor.** D-1, I-7, W-2900. p. 455, Sept., '27.

**V—The Two-Element Power Osiso.** C-2, D-2, I-7, W-4500. p. 507, Oct., '27.

**VI—The Multi-Element Oscillograph.** D-1, I-9, W-4700. p. 557, Nov., '27.

**VII—The Multi-Element Oscillograph and Power Osiso Arranged for Transmission Line Studies.** C-3, D-2, I-4, W-4800. p. 614, Dec. '27.

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**VIII—Auxiliary Apparatus for Staged Tests with the Multi-Element Oscillograph.** D-1, I-9, W-5590. p. 39, Jan., '28.

**IX—Polyphase Galvanometer Control for the Multi-Element Oscillograph.** I-9. W-4500. p. 102, Feb., '28.

**X—Sphere of Applications Expanded with New Galvanometers.** T-3, D-2, I-6, W-4650. p. 556, Nov., '28.

**Potential Transformer Connections for Three-Phase, Four-Wire Metering—L. D.** Price. T-3, D-5, W-3370. Vol. XXIV, p. 377, Aug., '27.

**A New Resistor for Use in Measurements of Impulse Voltages and Currents**—Edward Beck. I-5, W-900. Vol. XXV, p. 157, Mar., '28.

**Metering Load on Two Buses**—QB, 2335.

**Measuring High-Voltage Power**—QB, 2338.

**Two Synchronoscopes to Show the Same Reading**—QB, 2353.

**Metering Six-Phase Power**—QB, 2400.

**Current and Potential Transformers on Opposite Sides of Star-Delta Transformer Bank**—QB, 2453.

**Current and Potential Transformers on Opposite Sides of Delta-Delta Transformer Bank**—QB, 2460.

**Horse-Power of Motor**—QB, 2499.

**Shunts with Alternating-Current Instruments**—QB, 2531.

**Three-Phase Metering with Two Current Transformers**—QB, 2550.

**Compensating for the Inductive Component of Line Drop**—QB, 2569.

**Measuring Power in Two Feeders with One Meter**—QB, 2576.

**Three-Phase, Three-Wire Metering**—QB, 2683.

**Number of Leads for Temperature Indicators**—QB, 2702.

**Metering Three-Wire Circuit**—QB, 2731.

**Protection and Metering for Three, Three-Phase Transformers**—QB, 2756.

**Resonant Test Voltage**—QB, 2853.

## Meters

**Ball Type Kv-a Demand Meter**—B. H. Smith. C-5, I-10, W-1500. Vol. XXI, p. 112, Mar., '24.

**The Transmission of Meter Readings by the Impulse Method**—B. H. Smith. D-4, I-2, W-1080. Vol. XXI, p. 219, May, '24.

**Remote Metering by the Impulse and Condenser Method**—B. H. Smith. D-5, I-3, W-1150. Vol. XXI, p. 355, Aug., '24.

**The Osiso—A Single-Element Oscillograph of Camera Size**—J. W. Legg. I-7, W-1850. Vol. XXI, p. 564, Dec., '24.

**The Phase Rotation Indicator**—H. L. Hildenbrand. I-5, W-1000. Vol. XXIII, p. 57, Feb., '26.

**The Centrifugal Frequency Recorder**—F. S. Stickney. I-4, W-1750. Vol. XXV, p. 547, Nov., '28.

**Meter Springs.** W-400. Vol. XXV, p. 463, Sept., '28.

**Reactive Factor Meters Should Be Used with Converters.** W-150. Vol. XXV, p. 463, Sept., '28.

**Energy Required by Instrument Coils at 50 Cycles**—QB, 2458.

**Use of Small Induction Motor and Tachometer as a Frequency Meter**—QB, 2465.

**Ammeter without Transformer on High-Voltage Circuit**—QB, 2535.

**Mixture for Putting Glass in Indicating Instruments**—QB, 2544.

**Connections of Power-Factor Indicator**—QB, 2621.

**Power-Factor Meter Connections**—QB, 2694, 2766.

**Synchroscope Operation**—QB, 2750.

**Leaving Synchroscope in Circuit**—QB, 2767.

**Meter Accuracy**—QB, 2781.

**Synchroscope Connections**—QB, 2808.

**Ground Detectors**—QB, 2818.

**Meter Constants**—QB, 2831.

**Power-Factor Meter Testing**—QB, 2833.

**Ground Detectors**—QB, 2834.

**Correction of Radio Error**—QB, 2838.

**Peculiar Behavior of Ground Detector**—QB, 2844.

**Effect of High Voltage on Laboratory Instruments**—QB, 2882.

## VOLTMETERS AND AMMETERS

**Crest Voltmeters and Their Characteristics**—D. F. Miner. T-1, C-3, D-3, I-13, W-4000. Vol. XXII, p. 571, Dec., '25.

**Popularizing Instruments for Radio Use**—J. W. Legg. I-10, W-4540. Vol. XXIII, p. 9, Jan., '26.

**Ammeter Shunts for Large Capacity Circuits**—Paul MacGahan. W-500. Vol. XXV, p. 615, Dec., '28.

**Extending Range of Alternating-Current Voltmeter with Series Impedance**—QB, 2384.

**Reading Speed of D-C. Motor with Graphic Field Ammeter**—QB, 2733.

**BX Instruments Used on Radio Sets**—QB, 2746.

**Milliameter as A.C. and D.C. Voltmeter**—QB, 2825.

## WATTMETERS

**Pole-Type Metering Outfits**—T. H. Frankenberry. C-1, I-4, W-1000. Vol. XXIII, p. 426, Aug., '26.

**Methods of Metering Energy in Three-Phase, Four-Wire Systems**—Carl Oman. D-11, W-1980. Vol. XXIII, p. 445, Sept., '26.

**Registration of Demand Watthour Meter**—QB, 2318.

**Measurement of Three-Phase Power with Single-Phase Wattmeter**—QB, 2328.

**Meter Connections**—QB, 2360.

**Polyphase Connections**—QB, 2375.

**Watthour Meter Connections**—QB, 2378, 2497.

**Measuring Three-Wire Single-Phase**—QB 2405.

**Testing Wattmeters**—QB, 2411.

**Watthour Meter Discs**—QB, 2439.

**Three-Phase Four-Wire Meter**—QB, 2426, 2477, 2744.

**Determination of Power-Factor by Means of Polyphase Wattmeter**—QB, 2448.

**Watthour Meter Testing**—QB, 2472, 2529, 2737.

**Metering Combined Single and Three-Phase 110-200-400 Volt Service**—QB, 2590.

**Single-Phase Testing of Two-Element Watthour Meter**—QB, 2613.

**Watthour Meters Measuring Reverse Power**—QB, 2666.

**Constant of Wattmeter and Instrument Transformers**—QB, 2762.

**Meter Constants**—QB, 2794.

**Metering Three-Phase Power with One Meter**—QB, 2805.

**Vector Diagram for Single-Phase Load**—QB, 2816.

**Reactive Watthour Meters**—QB, 2845.

**Meter Vector Relations**—QB, 2866.

**Watthour Meter Connections**—QB, 2874.

## RELAYS

**A Phase Balance Current Relay of the Negative Phase Sequence Type**—J. V. Breisky. C-1, I-8, W-2820. Vol. XXI, p. 77, Feb., '24.

**Relay Practice**—H. H. Green. C-1, I-5, W-3750. Vol. XXI, p. 319, July, '24.

**The Automatic Network Relay**—John S. Parsons. C-3, I-4, W-4310. Vol. XXII, p. 339, July, '25.

**Relay Protection of Power-House Motors**—Ralph Kelly. D-3, I-3, W-2800. Vol. XXII, p. 438, Sept., '25.

**Protective Relays for Central Station Systems**—O. J. Bliss. D-7, W-4220. Vol. XXII, p. 578, Dec., '25.

**Development in the Impedance-Type Relay**—John V. Breisky and H. A. McLaughlin. C-1, D-4, I-4, W-3270. Vol. XXIV, p. 80, Feb., '27.

**Direct-Current Time-Delay Relays—Moving Vane Type**—John V. Breisky. C-1, I-8, W-2640. Vol. XXIV, p. 179, Apr., '27.

**Recent Developments in Automatic Network Relays**—John S. Parsons. C-5, D-2, I-2, W-3100. Vol. XXIV, p. 587, Dec., '27.

**The Grid Glow Tube Relay**—D. D. Knowles. C-2, I-4, W-2050. Vol. XXV, p. 176, Apr., '28.

**The Relaying Problems of a Typical Large Interconnection**—B. M. Jones. C-1, D-1, W-1100. Vol. XXV, p. 171, Apr., '28.

**Bimetal: The Temperature Sentinel**—H. E. Cobb. I-8, W-2750. Vol. XXV, p. 288, June, '28.

**A Thermal Accelerating Relay**—H. E. Cobb. C-1, D-1, I-6, W-1750. Vol. XXV, p. 345, July, '28.

**Applying Relays to Circuit-Breakers.** W-950. Vol. XXV, p. 415, Aug., '28.

**Relaying the 110 000 Volt System of the Edison Electric Illuminating Company of Boston**—William W. Edson. D-5, I-2, W-1450. Vol. XXV, p. 540, Nov., '28.

**The Functions of a Relay.** W-400. Vol. XXV, p. 199, Apr., '28.

**Connections for Differential Protection of Transformers**—QB, 2401.

**Differential Protection**—QB, 2407, 2487, 2493.

**Relay Connections**—QB, 2430, 2692.

**Relay and Watthour Meter Connections**—QB, 2497.

**Operation of Pulsating Current Relay**—QB, 2501.

**Operation of Hesitating Relay**—QB, 2515.

**Testing Overcurrent Induction-Type Relays**—QB, 2548.

**Setting of Differential Relays**—QB, 2554.

**Effect of Switching Out One of Two Transmission Lines Protected by CD Relay**—QB, 2557.

**Overspeed Protection of Motor-Driven Exciter**—QB, 2558.

**Overload Relay Connections**—QB, 2567.

**Differential Protection Tests**—QB, 2570.

**Differential Protection of Star-Delta Transformer Bank**—QB, 2574.

**Testing Relays**—QB, 2597.

**Determination of Current Setting on Relay**—QB, 2623.

**Protection of Parallel Transmission Lines by Means of Cross Connected CR Relays at Generating End and CR Relays Directly Connected at Receiving End**—QB, 2658.

**Relay Protection for Interstation Ties**—QB, 2660.

**Line Protection with Power Reversed**—QB, 2669.

**Protection with CD Relays**—QB, 2741.

**Protection for Generator Faults**—QB, 2745.

**Over-Current Relays**—QB, 2753.

**Operation of Differential Relays when Generators are Synchronized**—QB, 2759.

**Protection of a Loop**—QB, 2785.

**Phase Relationships in Reverse Power Relay**—QB, 2791.

**Differential Transformer Protection**—QB, 2827.

**Overcurrent Relays**—QB, 2842.

## THEORY

**Vector Methods of Analysis of Unsymmetrical Systems**—A. M. Dudley. D-3, W-2750. Vol. XXI, p. 339, July, '24.

**Analytical Solution of Networks**—R. D. Evans. D-23, W-10 170. Vol. XXI, p. 149, Apr., '24; p. 207, May, '24.

**Magnetic Analysis**—T. Spooner. C-12, D-2, I-1, W-5000. Vol. XXII, p. 113, Mar., '25. (E) Chas. R. Riker. W-900, p. 101.

**A Formula for Use in Calculating Repulsion of Coaxial Coils**—H. B. Dwight. I-1, W-1300. Vol. XXII, p. 389, Aug., '25.

**Demagnetization of Iron and Steel**—G. H. Cole. T-2, C-10, I-4, W-4160. Vol. XXIII, p. 289, June, '26.

**Short-Circuit Calculating Table of the Variable Resistor Unit, Direct-Current Type**—I. T. Monseth and R. DeCamp. T-3, D-3, I-5, W-4350. Vol. XXIII, p. 299, June, '26.

**Mapping Magnetic and Electrostatic Fields**—A. D. Moore. I-24, W-6110. Vol. XXIII, p. 355, July, '26. (E) W-450, p. 338.

**A Practical Application of Graphical Flux Mapping**—J. F. Calvert. I-11, W-2300. Vol. XXIV, p. 543, Nov., '27.

**Graphical Flux Mapping**—J. F. Calvert and A. M. Harrison. Vol. XXV.

**I—Theory and General Discussion.** I-10, W-2810. p. 147, Mar., '28.

**II, III and IV—Fields of Non-Salient Pole Synchronous Machines.** C-1, I-29, W-4600. p. 179, Apr.; p. 246, May; p. 362, July, '28.

**V—Direct-Current Motors and Generators.** I-7, W-1450. p. 399, Aug., '28.

**VI—Direct-Current Motor—Salient Pole Synchronous Machine—Universal Motor—Directional Element of a Reverse-Current Relay—Three-Pole Magnetic Contactor.** I-9, W-2400. p. 510, Oct., '28.

**Impedance of a Rotating Synchronous Machine to a Negative Sequence Voltage**—C. F. Wagner and A. Dovjikov. T-1, D-20, W-3680. Vol. XXIV, p. 117, Mar., '27.

**Distorted Asymmetric Wave Shapes**—R. D. Evans. (E) W-600. Vol. XXIV, p. 416, Sept., '27.

**Short-Hand Mathematics**—Chas. R. Riker. (E) W-350. Vol. XXV, p. 117, Mar., '28.

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**Symmetrical Components**—C. F. Wagner and R. D. Evans. Vol. XXV.

**I—Resolution of Vectors Into Symmetrical Co-ordinates.** D-9, W-5800. p. 151, Mar., '28.

**II—Resolution of Three Vector Products into Products of Their Symmetrical Components.** D-2, W-3250. p. 194, Apr., '28.

**III**—Calculation of Unbalanced Faults. D-7, W-3650. p. 307, June, '28.

**IV—Calculation of Faults on Systems with Lumped Constants.** D-3, W-2550. p. 359, July, '28.

**Induced Voltages in Conductors**—H. B. Dwight. I-1, W-3000. Vol. XXV, p. 173, Apr., '28.

**Effects of Corona in Various Gases on Insulation and Losses**—C. F. Hill. C-1, I-2, W-550. Vol. XXV, p. 402, Aug., '28.

**The Proportionality Chart**—F. Paulsen. C-3, W-850. Vol. XXV, p. 416, Aug., '28.

**Phase Displacement in Inductive Circuits**—QB, 2560.

**Vector Solution of Three-Phase Problem**—QB. 2586.

**Units of Magnetomotive Force**—QB. 2591.

**Vector Conventions**—QB, 2596.

**Voltage Induced in Coil on Opening Circuit**—QB, 2631.

**Four-Wire Neutral Current with Single-Phase Secondary Load**—QB. 2633.

**Direction of Earth's Field**—QB, 2678.

**Collecting Ozone**—QB, 2679.

**Current in Rotating Disc in a Magnetic Field**—QB, 2687.

**Short-Circuit Calculation**—QB, 2768.

**Commercial Efficiency Formula**—QB, 2779.

**Equations for Instantaneous Voltage and Current**—QB, 2855.

# GENERATION

**(AND ALL PARTS OF ROTATING MACHINES)**

## GENERAL

**Surge Generating Equipment**—D. F. Miner, C-2, D-14, I-7, W-5360. Vol. XXIII, p. 596. Dec., '26.

**Effect of Altitude on Rating**—QB, 2718, 2751.

## POWER PLANTS

**The Function of a Base Load Station**—W. L. Abbott. (E) W-600. Vol. XXI, p. 194, May, '24.

**Present Tendencies in the Design of Large Power Plants**—W. C. L. Eglin. (E) W-150, Vol. XXI, p. 198, May, '24.

**Power Plant Unit Costs and Their Engineering Significance**—Linn Helander. T-3, C-3, D-1, W-2820. Vol. XXI, p. 285, June, '24.

(E) A. H. McIntire. W-550, p. 259.

**Relay Protection of Power-House Motors**—Ralph Kelly, D-3, I-3, W-2800. Vol. XXII, p. 438, Sept., '25.

**Electric Power for Chemical Plants**—J. L. McK. Yardley. T-6, I-4, W-9800. Vol. XXIII, p. 113, Mar., '26.

**An Emergency Power Unit.** W-200. Vol. XXV, p. 430, Sept., '28.

**Computing Generator Size**—QB, 2722.

**Transmission System Speed Control**—QB, 2804.

### DESCRIPTIONS

**165 000 Kw Turbine Generator for Hell Gate**—H. J. Hanzlik. I-5, W-3150. Vol. XXV, p. 274, June, '28.

**The New Cahokia Power Station of the Union Electric Light & Power Co., of Illinois**—Peter Junkersfeld. I-10, W-6500. Vol. XXI, p. 232, May, '24.

**New 40 000 Kilowatt Turbines for the Duquesne Light Company**—J. D. Schmidt. I-5, W-1850. Vol. XXV, p. 36, Jan., '28.

**The "Why" in Hudson Avenue**—John C Parker. (E) W-1500. Vol. XXII, p. 150, Apr., '25.

**A Perspective View**—Chas. R. Riker. (E) W-550. Vol. XXII, p. 152, Apr., '25.

**The Fundamental Plan in the Electrical Design of the Hudson Avenue Generating Station of the Brooklyn Edison Company**—H. R. Woodrow. D-3, W-1520. Vol. XXII, p. 153, Apr., '25.

**The Construction and Mechanical Features of the Hudson Avenue Station of the Brooklyn Edison Company**—J. N. Landis. D-2, I-17, W-5950. Vol. XXII, p. 155, Apr., '25.

**The Electrical Circuits and Switching Equipment of the Hudson Avenue Station of the Brooklyn Edison Company**—E. A. Hester. C-1, D-5, I-15, W-9900. Vol. XXII, p. 166, Apr., '25.

**Fourth Unit Extension for the Hudson Avenue Generating Station of the Brooklyn Edison Company**—H. R. Woodrow. C-2, W-980. Vol. XXII, p. 855, July, '25.

**Hydro-Electric Generator Equipment for Muscle Shoals**—R. A. McCarty. I-7, W-1460. Vol. XXI, p. 140, Apr., '24.

**Automatic Hydro-Electric Plant of the San Gorgonio Power Company**—P. B. Garrett. I-4, W-2480. Vol. XXII, p. 286, June, '25.

**Seal Beach Power Station—Los Angeles Gas & Electric Corporation, Los Angeles, California**—J. G. Rollow and C. W. E. Clarke. D-8, I-9, W-1980. Vol. XXII, p. 281, June, '25.

**Automatic Control of Hydro-Electric Plants on the Peshtigo River**—A. G. Carson and E. D. Lilja. I-5, W-2440. Vol. XXIII, p. 168, Apr., '26.

**Heating a Large Generator Rotor by Induction at Big Creek Power House of the California Edison Co.**—G. C. Heckman. C-3, D-1, I-1, W-1800. Vol. XXIII, p. 467, Sept., '26.

## Substations

**Automatic Substations for Edgar Thomson Works of the Carnegie Steel Company**—R. J. Wensley. I-2, W-1650. Vol. XXI, p. 409, Sept., '24.

**The Charleroi Substation of the West Penn Power Company**—Geo. S. Humphrey. C-1, D-2, I-14, W-2500. Vol. XXI, p. 498, Nov., '24.

(E) Chas. R. Riker. W-500. p. 497

**Kings Highway Substation of the Brooklyn Edison Company**—C. M. Gilt. D-1, I-7, W-3240. Vol. XXII, p. 521, Nov., '25.

**Full Automatic Phase Modifier Station—Northwestern Electric Co., Portland, Oregon**—E. F. Pearson and T. Perry, I-4, W-1460. Vol. XXIII, p. 154, Apr., '26.

**Automatic Substations on Pacific Electric System**—S. H. Anderson. T-2. I-5, W-1740. Vol. XXIII, p. 496, Oct., '26.

**Automatic Substation Equipment of the Staten Island Rapid Transit Railway**—J. S. Hagan. D-1, I-6, W-2620. Vol. XXIII, p. 499, Oct., '26.

**The Avenue T Automatic Supervisory Controlled Substation of the New York Rapid Transit Co., Brooklyn, New York**—R. I. Longwell. T-1, D-1, I-23, W-5650. Vol. XXIII, p. 503, Oct., '26.

**Automatic Railway Substations in Japan**—C. E. Valentine and W. L. Newmeyer. D-1, I-6, W-4600. Vol. XXIII, p. 513, Oct., '26.

**Automatic Substations on the Montreal & Southern Counties Railway**—R. N. Godin. I-5, W-1350. Vol. XXIII, p. 521, Oct., '26.

**Ventilation and Noise Controls of Substation Machinery**—F. T. Hague. I-5, W-3630. Vol. XXI, p. 107, Mar., '24.

**Sound-Proof Automatic Substations**—R. L. Hall, I-5, W-2300. Vol. XXIV, p. 273, June, '27.

**Automatic Switching Equipment for Mining Substations**—S. M. Dougherty. I-5, W-2450. Vol. XXV, p. 214, May, '28.

**Control of Outdoor Substation and Layout of Feeders**—QB, 2802.

## DYNAMOS AND MOTORS

### General

**The Business of Designing Electrical Machinery**—F. D. Newbury. T-2, I-3, W-6250. Vol. XXV, p. 267, June, '28.

**Economic Principles of Design**—A. M. Dudley. (E) W-1300. Vol. XXV, p. 421, Sept. '28.

**A Survey of Heavy Electrical Machinery Development**—F. D. Newbury. W-3540. Vol. XXIII, p. 190, Apr., '26.

**Selecting Motors for Frequent Starting—Importance of Armature Speed and Moment of Inertia**—C. B. Hathaway. C-20, W-1550. Vol. XXII, p. 89, Feb., '25.

**Recent Developments in Electrical Laboratory Equipment**—F. S. Wheeler. C-4, D-2, I-7, W-3470. Vol. XXII, p. 544, Nov., '25.

**The Influence of Density upon the Weight and Volume of Air which Passes through an Electrical Machine**—C. J. Fechheimer. T-1, C-2, W-3150. Vol. XXIII, p. 63, Feb., '26.

**Steel-Mill Motor Ventilation**—R. T. Thornton. C-1, I-5, W-1840. Vol. XXIII, p. 284, June. '26.

**Maximum Efficiency of Motors**—E. R. Martin. C-1, W-1080. Vol. XXIII, p. 161. Apr., '26.

**Characteristics of Generators and Motors for Gas-Electric Traction**—C. A. Atwell, C-4, D-2, I-3, W-2880. Vol. XXIII, p. 363, July. '26.

**Soldering Joints in Electrical Windings—Pouring vs. Soldering Iron**—M. Sandfield. I-6, W-500. Vol. XXI, p. 534, Nov., '24.

**Sheet-Steel Enclosing End Bells**—R. M. Casper. I-2, W-260. Vol. XXII, p. 224, May, '25.

**What Is a Reasonable Stock of Renewal Parts?**—A. G. Ahrens. W-2500. Vol. XXII, p. 432, Sept., '25.

**Care and Maintenance of Renewal Parts for Electrical Equipment**—G. P. Wilson. W-900. Vol. XXIV, p. 333, July, '27.

**Changing from Cast Iron and Steel to Fabricated Steel**—H. V. Putman and C. C. Brinton. I-16, W-3050. Vol. XXV, p. 333, July, '28.

**How to Clean Grease and Oil from Windings.** W-600. Vol. XXV, p. 250, May, '28.

**Drying Out**—QB, 2389.

**E. M. F. Formulas for Generator and Transformer**—QB, 2469.

**Calculating Motor Output**—QB, 2547.

**R. M. S. Method of Motor Rating**—QB, 2638.

**Heat Radiation from Motor**—QB, 2760.

**Dynamic Braking**—QB, 2769.

### GENERAL TESTS

**Methods of Testing Electrical Apparatus.**

**I—General Instructions.** T-1, C-1, W-3650 Vol. XXII, p. 41, Jan., '25.

(E) A. H. McIntire. W-600, p. 2.

**II—Testing Equipment.** T-1, I-6, W-2900. Vol. XXII, p. 91, Feb., '25.

**III—Testing Equipment** C-2, I-2, W-3630. Vol. XXII, p.. 136, Mar., '25.

**IV—Resistance Measurements.** I-10. W-4400. Vol. XXII, p. 191, Apr., '25.

**V—Temperature Measurements.** C-1, I-6, W-3960. Vol. XXIII, p. 43, Jan., '26.

**VI—Setting Up and Preliminary Adjustments of Rotating Machines.** C-1, I-1, W-5150. Vol. XXIII, p. 83, Feb., '26.

**VII—Losses of Rotating Machines.** D-2, W-3890. Vol. XXIII, p. 131, Mar., '26.

**VIII—Operation Under Load.** I-2, W-1880. Vol. XXIII, p. 194, Apr., '26.

**IX, X, XI, and XII—Direct-Current Generators and Motors.** T-15, C-10, D-9, W-12, 230. Vol. XXIII, p. 326, June, '26; p. 375, July, '26; p. 421, Aug., '26; p. 478, Sept., '26.

**XIII and XIV—Railway, Vehicle and Mine Motors.** T-7, C-5, D-1, W-4130. Vol. XXIII, p. 537, Oct., '26; p. 580, Nov., '26.

**XV—Alternating-Current, Single - Phase, Series Railway Motors.** T-4, C-4, D-1, W-1800. Vol. XXIII, p. 620, Dec., '26.

**XVI, XVII, XVIII and XIX—Synchronous Generators and Motors.** T-7, C-10, D-17, W-11 400. Vol. XXIV, p. 43, Jan.; p. 87, Feb.; p. 183, Apr.; p. 226, May, '27.

**XX and XXI—Synchronous Converters.** T-1, C-3, D-3, I-1, W-4400. Vol. XXIV, p. 356, July; p. 405, Aug., '27.

**XXII, XXIII and XIV—Induction Motors.** T-10, C-3, D-6, W-11 700. Vol. XXIV, p. 462, Sept.; p. 569, Nov.; p. 625, Dec., '27.

**XXV and XXVI—Transformers.** D-3, I-10, W-8150. Vol. XXV, p. 410, Aug.; p. 457, Sept., '28.

**XXVII—Temperature Tests.** I-4, W-2400 Vol. XXV, p. 516, Oct., '28.

**XXVIII—Insulation Tests and Tests on Single-Phase Transformers Not Self Cooled.** T-1, D-1, W-4050. Vol. XXV, p. 563, Nov., '28.

**XXIX—Three-Phase Transformers.** T-1, C-1, D-4, I-2, W-3950. Vol. XXV, p. 608, Dec., '28.

**A High-Power Laboratory for Testing Oil Circuit Breakers**—W. R. Woodward. D-1, I-9, W-2740. Vol. XXIII, p. 102, Mar., '26.

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**An Extension of the High-Power Testing Laboratory**—W. R. Woodward. I-3, W-1650. Vol. XXV, p. 139, Mar., '28.

**A Laboratory for Testing the Interrupting Capacities of D. C. Circuit Breakers**—W. R. Woodward. I-5, W-1500. Vol. XXIV, p. 502, Oct., '27.

**Low-Voltage Testing Outfits**—H. M. Sanders. D-5, I-5, W-2720. Vol. XXIII, p. 604, Dec., '26.

**A New Portable Oil Testing Set**—A. M. Wiggins. C-1, I-3, W-1150. Vol. XXV, p. 301, June, '28.

**Stroboscopic-Neon Lamp Method for Measuring the Slip of Induction Motors**—Carl C. Nelson. I-4, W-1050. Vol. XXV, p. 163, Mar., '28.

**Load Test on Repaired Railway Motors**—ROD, XXI, p. 346.

**Testing Railway Motors under the Car**—ROD, XXI, p. 445.

**Deceleration Method of Determining Losses**—QB, 2485.

**Distribution of Losses in Direct-Current Generator**—QB, 2575.

**Calculating Efficiency of D-C. Motors**—QB 2707.

**Efficiency of Water-Wheel Generators**—QB, 2708.

**Motor Insulation Test**—QB, 2738.

**Resonant Test Voltage**—QB, 2853.

### ARMATURES

(Except commutators.)

**The Reason for Chorded Windings**—R. Ludwig. C-2, W-1400. Vol. XXV, p. 47, Jan. 28.

**Construction and Advantages of High-Grade Armature Coils**—ROD, XXII, p. 361.

**Armatures Cores for Railway Motors**—ROD, XXIV, p. 359.

**Spiders for Railway Motor Armatures**—ROD, XXIV, p. 468.

**Winding a Direct-Current Motor for Alternating-Current**—QB, 2333.

**Reconnecting Direct-Current Armature**—QB, 2327, 2492.

**Rewinding a 125 Volt Armature for 650 Volts**, QB, 2331.

**Heating of Armature Bands**—QB, 2362.

**Trouble in Armature with Idle Coil**—QB, 2403.

**Stresses on Rotor Bands**—QB, 2494.

**Rewinding Shunt Motor for Half-Voltage**—QB, 2534.

**Multiple Versus Series Armature Winding**—QB, 2555.

**Treatment of 2200 Volt Coils**—QB, 2559.

**Wrapping Coils**—QB, 2561.

**Protection of Motor Coils against Acid Fumes**—QB, 2566.

**Effect of Reversed Coil in Loop-Wound Armatures**—QB, 2572.

**Limitations of Series Wound Armatures**—QB, 2581.

**Laying Out Direct-Current Armature Windings**—QB, 2598.

### BEARINGS

**Waste-Packed Bearing Design and Operation**—C. Bethel. T-1, C-1, I-3, W-2500. Vol. XXI, p. 115, Mar., '24.

**Renewal Bearings of Graded Diameters for Railway Motors**—J. F. Curtis. I-1, W-890. Vol. XXII, p. 499, Oct., '25.

**The Use of Ball Bearings on Mine Locomotive Motors**—C. A. Atwell. C-1, I-7, W-2500. Vol. XXI, p. 513, Nov., '24.

**Bearing Currents**—Origin and Prevention—C. T. Pearce. I-13, W-3400. Vol. XXIV, p. 372, Aug., '27.

**Babbitt Metal**—ROD, XXII, p. 515.

**Improved Methods of Lubricating Railway Motor Bearings**—ROD, XXIII, p. 196.

**Reclaiming Used Oil and Waste**—ROD, XXIII, p. 541.

**Testing Babbitt-Lined Bearing Shells**—ROD, XXIV, p. 188.

**Air-Gap of Induction Motor**—QB, 2341.

**Cause of Rapid Wear of Motor Bearings**—QB, 2482.

**Bearing Pressure and Bearing Loss**—QB, 2832.

### BRUSHES

**Sidewear of Brushes in Railway Motors**—F. W. McCloskey. I-7, W-1660. Vol. XXII, p. 491, Oct., '25.

**Direct-Current Brush Arm Capacity.** W-750. Vol. XXV, p. 109, Feb., '28.

**Side Wear of Carbon Brushes**—ROD, XXIV, p. 91.

**Brushholder Repair Work**—ROD, XXII, p. 140, 197.

**Insulation of Railway Motor Brush-Holders**—ROD, XXIV, p. 525.

**Cutting Slots in Brushes**—QB, 2710.

**Brush Sparking**—QB, 2793.

### COMMUTATORS and COLLECTOR RINGS

**Types of Commutator Construction**—P. F. Pippitt. I-6, W-1360. Vol. XXIII, p. 565, Nov., '26.

**Commutator Flashovers in Generators and Motors**—J. H. Harvey. I-6, W-1500. Vol. XXIII, p. 583, Nov., '26.

**Cleaning Commutator Bars**—A. C. Roe. W-500. Vol. XXV, p. 568, Nov., '28.

**Commutation Trouble in 150 Kw Generator**—QB, 2466.

**Grinding Commutator**—QB, 2601.

**Commutator Blackening**—QB, 2713.

**Wearing of Slip Rings**—QB, 2719.

**Refinishing Worn Commutators**—QB, 2752.

### FIELD WINDINGS

**Improved Field Coil Insulation for Large Salient-Pole Machines**—R. M. Casper. I-6, W-600. Vol. XXII, p. 24, Jan., '25.

**Impregnating Railway Motor Field Coils** ROD, XXII, p. 95

**Construction and Repair of Field Coils**—ROD, XXII, p. 309.

**Field Coil Springs, Washers and Shields**—ROD, XXIII, p. 585.

**Putting Field Coils in Box-Frame Motors**—ROD, XXIV, p. 140.

**Testing of Series Field Coils**—QB, 2415.

**Discharge Resistance for Synchronous Motors**—QB, 2427.

**Burn Out of Turbogenerator Field**—QB, 2629.

**Permalloy for Field Pole Cores**—QB, 2704.

**Aluminum and Copper Coils**—QB, 2754.

### SHAFTS

**Mounting Rotors on Shafts in the Field**—E. L. Doty. W-1800. Vol. XXII, p. 220, May, '25.

(E) Chas. R. Riker. W-400, p. 201.

**Heating a Large Generator Rotor by Induction.**—Geo. C. Heckman. C-3, D-1, I-1, W-1800. Vol. XXIII, p. 467, Sept., '26.

**Pinion Seats on Railway Motor Shafts**—ROD, XXIV, p. 302.

**Failure of Coupling Bolts**—QB, 2410.

**Shaft Deflection**—QB, 2425.

## Direct Current

**Standard Line of Direct-Current Machines Fabricated by Arc Welding**—R. S. Marthens, C. C. Brinton and F. T. Hague. I-8, W-4000. Vol. XXV, p. 575, Dec., '28.

**Direct-Current Dynamometers**—Scott Hancock. C-3, D-2, W-3630. Vol. XXII, p. 385, Aug., '25.

**Dynamic Braking with Different Types of Motors**—QB, 2769.

### SHUNT AND COMPOUND

**Characteristics of Direct-Current Motors**—R. W. Owens. C-8, I-2, W-4480. Vol. XXIII, p. 37, Jan., '26.

**Stability of Direct-Current Generators at Low Voltages and When Used with Voltage Regulators**—C. Lynn, C-4, D-1, I-1, W-3940. Vol. XXI, p. 304, July, '24.

**Some Problems of Parallel Operation of Direct-Current Generators**—I. C. Smith. D-8, I-10, W-4070. Vol. XXIII, p. 407, Aug., '26.

**Parallel Operation of Direct-Current Generators**—QB, 2675.

**A New Arc Welding Generator**—A. M. Candy. C-2, D-2, I-1, W-1750. Vol. XXI, p. 413, Sept., '24.

**Effect of Open Circuit in Balance Coil of Three Wire Generator Using Two Balance Coils**—C. T. Pearce. D-3, W-550. Vol. XXI, p. 486, Oct., '24.

**Direct-Current Generators for Battery Charging**—J. A. Elzi. C-3, I-1, W-2710. Vol. XXIII, p. 351, July, '26.

**Theory of the Action of Equalizer Connections in Lap Windings**—A. D. Moore. I-3, W-2850. Vol. XXIII, p. 624, Dec., '26.

**Selecting the Most Desirable Type of Direct-Current Generator**—Scott Hancock. C-7, I-1, W-4000. Vol. XXV, p. 141, Mar., '28.

**Characteristics of Direct-Current Motors and Generators for Diesel Electric Ship Propulsion**—C. T. Pearce. I-7, W-2450. Vol. XXV, p. 135, Mar., '28.

**Enclosed, Fan Cooled Motors**—C. C. Nelson. I-4, W-550. Vol. XXV, p. 385, Aug., '28.

(E) Chas. R. Riker. W-550, p. 373.

**Operation of Direct-Current Motors in Parallel and Series with Different Types of Load**—C. T. Pearce. C-6, W-3750. Vol. XXV, p. 581, Dec., '28.

**Generator Characteristics.** C-1, W-600. Vol. XXV, p. 159, Mar., '28.

**A High Temperature Motor.** W-300. Vol. XXV, p. 186, Apr., '28.

**Changing From 250 to 125 Volts**—QB, 2314, 2321.

**Increasing Torque**—QB, 2336.

**Changing the Polarity of a Direct-Current Generator**—QB, 2329.

**Location of Three-Wire Generative Circuit Breakers**—QB, 2348.

**Operation of Direct-Current Motor on Alternating Current**—QB, 2396.

**Charging Batteries with Differential Compound Generator**—QB, 2408.

**Use of Small Direct-Current Motor as a Generator**—QB, 2436.

**Size of Field Rheostat for Shunt Generator**—QB, 2505

**Loss of Load by Shunt Generators Operating in Parallel**—QB, 2606.

**Generator Field Current**—QB, 2611.

**Compound Generator Connections**—QB, 2627.

**Motor Winding**—QB, 2672.

**Operation from No-Load Saturation Curve**—QB, 2689.

**Paralleling Converters and D-C. Generators**—QB, 2711.

**Reversing Compound Generator**—QB, 2712

**Reading Speed of Direct-Current Motor with Graphic Field Ammeter**—QB, 2733.

**Reversing the Direction of a Direct-Current Generator**—QB, 2809.

**Three-Wire Direct-Current Generator with One Neutral Ring**—QB, 2871.

**High-Speed Dry-Battery-Operated Motor**—QB, 2880.

### EXCITERS

**Quick-Response Excitation for Alternating-Current Synchronous Machinery**—C. A. Powel. C-5, D-4, I-1, W-3880. Vol. XXIV, p. 157, Apr., '27.

**Practical Considerations Affecting Quick-Response Excitation for Salient Pole Machines**—P. H. Robinson. C-12, I-1, W-4000. Vol. XXV, p. 65, Feb., '28.

**System Stability with Quick-Response Excitation and Voltage Regulators**—J. H. Ashbaugh and H. C. Nycum. C-4, I-2, D-1, W-3750. Vol. XXV, p. 504, Oct., '28.

**Determining Time Constant**—QB, 2553.

**Improving Time Constant**—QB, 2571.

**Overspeed Protection of Motor-Driven Exciter**—QB, 2558.

**Time Constants of Exciters**—QB, 2587.

### SERIES

**Motors for Commercial Electric Vehicles**—C. A. Atwell. C-4, I-2, W-1360. Vol. XXI, p. 33, Jan., '24.

**The Importance of Efficient Lubrication of Railway Motors**—C. Bethel. C-5, I-4, W-3700. Vol. XXI, p. 467, Oct., '24.

**The Use of Ball Bearings on Mine Locomotive Motors**—C. A. Atwell. C-1, I-7, W-2500. Vol. XXI, p. 513, Nov., '24.

**Protecting Railway Motors from Overheating.** I-2, W-500. Vol. XXV, p. 46, Jan., '28.

**Why Different Temperature Ratings for Railway Motors.** W-200, Vol. XXV, p. 109, Feb., '28.

**Ventilation of Railway Motors**—F. Paulsen. W-1050. Vol. XXV, p. 251, May, '28.

**Taking off Railway Motor Pinions**—ROD, XXI, p. 126.

**Insulating a Railway Motor Armature**—ROD, XXI, p. 535.

**Machining Split-Frame Motors at Bearing and Housing Seats**—ROD, XXI, p. 300.

**Motor Covers and Axle Shields**—ROD, XXIII, p. 484.

**Direct-Current Railway Motor Ratings**—ROD, XXIII, p. 627.

**Dual Ventilation for Railway Motors**—ROD, XIV, p. 630.

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**Revamping Old Railway Motors with Modern Renewal Parts**—ROD, XXV, p. 201.

**Principle of Operation of a Series Arc Generator**—QB, 2323.

**Fan Motor Operation**—QB, 2715.

**COMMUTATING POLE**

**The Number of Commutating Poles Used in Direct-Current Machines**—Joseph A. Elzi. D-3, W-1900. Vol. XXII, p. 129, Mar., '25.

**The Purpose and Construction of Commutating Poles**—H. R. Elker. I-1, W-1140. Vol. XXIII, p. 555. Nov., '26.

**Commutating Field Adjustment.** W-400. Vol. XXV, p. 108, Feb., '28.

**Relative Polarity of Main and Commutating Poles**—QB, 2490.

**Flux Distortion**—QB, 2580.

**Unequal Air Gaps**—QB, 2680.

**Number of Commutating Poles with Lap Windings**—QB, 2720.

**Commutating Pole Windings**—QB, 2782.

## Alternating Current

**Impedance of a Rotating Synchronous Machine to a Negative Sequence Voltage**—C. F. Wagner and A. Dovjikov. T-1, D-20, W-3680. Vol. XXIV, p. 117, Mar., '27.

**Quick-Response Excitation for Alternating-Current Synchronous Machinery**—C. A. Powel. C-5, D-4, I-1, W-3880. Vol. XXIV, p. 157, Apr., '27.

**A Million Volt Rectified Surge Generator**—D. F. Miner, C-2, D-6, I-3, W-3000. Vol. XXIV, p. 287, June, '27.

**Saturation Data on Alternating-Current Machinery**—QB, 2540.

**Distribution Factor**—QB, 2865.

**ALTERNATORS**

**Multiple Path Radial Ventilation**—M. D. Ross. T-1, C-4, I-6, W-2300. Vol. XXI, p. 540. Dec., '24.

**Parallel Operation of Direct-Connected Auxiliary Generators**—H. B. Seeley. D-6, W-2950. Vol. XXI, p. 387, Aug., '24.

**The Application of Decrement Factors in Short-Circuit Studies**—W. R. Woodward. T-5, C-1, D-3, W-2390. Vol. XXIII, p. 213, May, '24.

**High-Frequency Alternators**—C. M. Laffoon. T-1, C-8, I-5, W-2200. Vol. XXI, p. 416. Sept., '24.

**Recent Developments in Hydro-Electric Generators**—F. D. Newbury. T-1, I-11, W-2730. Vol. XXII, p. 210, May, '25.

**Improved Damper Windings for High-Speed Synchronous Machines**—R. M. Casper. I-2, W-400. Vol. XXII, p. 196, Apr., '25.

**Hot-Spot Temperature Measurement in Alternating-Current Generators**—S. L. Henderson. I-10, W-3260. Vol. XXIII, p. 95, Mar., '26.

**Transposed Armature Coils in Alternating-Current Generators**—S. L. Henderson. C-1, I-7, W-2860. Vol. XXIII, p. 348, July, '26.

**Stability of Alternating-Current Turbine Generators with Fluctuating Loads**—John Strasser. C-12, I-6, W-4700. Vol. XXIII, p. 413, Aug., '26.

(E) S. L. Henderson. W-300. p. 393.

**Types of High-Frequency Alternators**—J. F. Calvert. D-5, I-3, W-1880. Vol. XXIV, p. 36, Jan., '27.

**Load Division between Alternators**—F. D. Newbury. C-2, I-1, W-1900. Vol. XXIV, p. 211, May, '27.

**Trends in Turbine Generator Development**—F. D. Newbury. C-2, I-20, W-3100. Vol. XXIV, p. 334, July, '27.

**A New Type of Turbogenerator Rotor Insulation**—M. D. Ross. I-6, W-1350. Vol. XXV, p. 63, Feb., '28.

**Generator Saturation Curves at Leading Power-Factor**—QB, 2366.

**Damping Effect of Copper Rings Placed Around Pole Tips**—QB, 2376.

**Operation of Alternator Connected to an Unloaded Trannsmission Line**—QB, 2383.

**Cross-Star Connection**—QB, 2474.

**Inherent Reactance of Alternators**—QB, 2500.

**Lifting Water-Wheel Generators**—QB, 2503.

**Alternator Field Discharge Resistor**—QB, 2504.

**No Load Excitation of Turbo-Generator**—QB. 2533.

**Performance of Three-Phase Generator with Unbalanced Load**—QB, 2537.

**Protection against High Voltage Due to Open Circuit in Alternator Field**—QB, 2548.

**Reconnecting Three-Phase Alternator for Single-Phase**—QB, 2545.

**Effect of Alternator Short-Circuit on Excitation**—QB, 2562.

**Generator Reactance Data**—QB, 2577.

**Distribution of Short-Circuit Currents in Parallel Alternators**—QB, 2578.

**Effect of Grounded Secondary on Generator with Grounded Neutral**—QB. 2589.

**Synchronizing Generators**—QB. 2600.

**Conversion of Direct-Current Motor Into Alternating-Current Generator**—QB, 2602.

**Burn Out of Turbogenerator Field**—QB, 2629.

**Changing D.C. Motor to A. C. Generator**—QB. 2636.

**Opening Field Circuit of Large Alternator Carrying Load**—QB, 2640.

**Generator Losing Voltage**—QB. 2641.

**Number of Leads for Temperature Indicators**—QB, 2702.

**Efficiency of Water-Wheel Generators**—QB, 2708.

**Effect of Altitude on Generator Rating**—QB, 2718.

**Grounding Generator Neutral**—QB, 2721.

**Hunting**—QB, 2870.

**Operation of Bleeder-Turbine Driven Generator**—QB, 2875.

**Noise from Lightly Loaded Alternator**—QB, 2883.

**INDUCTION**

**The Polyphase Induction Generator**—D. F. Alexander. C-5, I-4, W-2250. Vol. XXV, p. 376, Aug., '28.

**High Frequency Alternators**—C. M. Laffoon. T-1, C-8, I-5, W-2200. Vol. XXV, p. 416, Sept., '24.

### *Parallel Operation*

**Alternating-Current Generators in Parallel**—QB, 2491.

**SYNCHRONOUS MOTORS**

**Pulsations in Power Due to Synchronous Motor Driven Compressors**—Quentin Graham. C-3, I-2, W-1220. Vol. XXI, p. 70, Feb., '24.

**Use of Synchronous Condensers with Three-Winding Transformers**—R. C. Bergvall. D-3, W-1700. Vol. XXI, p. 205, May, '24.

**The Control of Synchronous Motors**—H. D. James and J. H. Graybill. D-2, I-2, W-3480. Vol. XXI, p. 335, July, '24.

**The Synchronous Motor in Steel-Mill Service**—D. W. Dean. C-5, I-5, W-3900. Vol. XXI, p. 428, Sept., '24.

**A New High-Torque Synchronous Motor**—Quentin Graham. C-1, I-6, W-1320. Vol. XXIII, p. 30, Jan., '26.

**The Correction of Power-Factor by the Use of Synchronous Motors**—P. C. Jones. C-2, D-1, W-1730. Vol. XXIII, p. 99, Mar., '26.

**Full Automatic Phase Modifier Station—Northwestern Electric Co., Portland, Oregon**—E. F. Pearson and Tom Perry. I-4, W-1460. Vol. XXIII, p. 154, April, '26.

**Automatic Control for Synchronous Condensers**—C. C. Levy, D-1, I-5, W-2740. Vol. XXIII, p. 150, Apr., '26.

**Operation of Synchronous Motor as Part of a Set**—R. L. Findley. T-1, C-14, W-2200 Vol. XXIV, p. 198, May, '27.

**The Industrial Synchronous Motor**—C. D. Kester (E) W-1200. Vol. XXIV, p. 531, Nov., '27.

**Synchronous Motor Applications in the Mining Industry**—H. Speight. D-1, I-9, W-1900. Vol. XXV, p. 219, May, '28.

**Magnetic Control for Synchronous Motors**—D. E. Inman. D-3, I-7, W-4050. Vol. XXV, p. 431, Sept., '28.

**Baby Synchronous Motors.** I-1, W-100. Vol. XXV, p. 199, Apr., '28.

**Drying Out Synchronous Motors**—QB, 2339.

**Effect of Synchronous Condenser on Line Voltage**—QB, 2392.

**Reconnecting 2200 Volt Motor for 440 Volts**—QB, 2394.

**Operation of 85 Kw Alternator as Synchronous Motor**—QB, 2413.

**Discharge Resistance for Synchronous Motors**—QB, 2427.

**Operating Characteristics**—QB, 2432.

**Synchronous-Motor Operation of Alternating-Current Generator**—QB, 2438.

**Capacity for Power-Factor Correction**—QB, 2445.

**Parallel Operation of Synchronous Frequency-Changer Sets**—QB, 2512.

**Starting Characteristics of Synchronous Motor-Generator Set**—QB. 2582. 2681.

**Starting Synchronous Motors**—QB. 2608.

**Brass Shims behind Pole Pieces**—QB, 2616.

**Y-Connected Synchronous Motor with No Neutral**—QB, 2661.

**Starting Synchronous Motor**—QB. 2665.

**Circle Diagram**—QB. 2682.

**Losses in Synchronous Condenser**—QB, 2690.

**Power-Factor of Industrial Plant**—QB, 2732.

**Synchronous Motor Field Protection**—QB. 2775.

**Notched-Rotor Synchronous Motors**—QB, 2783.

**Changing Motor Voltage**—QB, 2813.

**FREQUENCY CHANGERS**

**A 35 000 Kw Synchronous Frequency Changer Set**—M. W. Smith. I-4, W-1970. Vol. XXI, p. 343, July, '24.

**A 49 000 Kv-a Frequency Converter Set**—R. A. McCarty. C-3, I-3. W-1090. Vol. XXIII, p. 339, July, '26.

**Variable-Ratio Frequency-Changer Sets**—C. W. Kincaid. D-6, I-1, W-4350. Vol. XXV, p. 279, June, '28.

**Dual-Frequency Calender Drive**—S. G. Nottage. C-1, I-3, W-1750. Vol. XXV, p. 500, Oct., '28.

**A New 30 000 Kv-a Frequency Changer.** W-150. Vol. XXV. p. 284, June, '28.

**Paralleling Frequency Changers**—QB, 2795.

**Frequency-Changer Exciter Voltage**—QB, 2801.

**INDUCTION MOTORS**

**Change-Speed Induction Motors**—C. W. Kincaid. T-1, D-19, I-1, W-4160. Vol. XXI, p. 357, Aug., '24.

**Some Accessories Often Used with Large Induction Motors**—D. F. Alexander. D-2, I-12, W-3970. Vol. XXIV, p. 14, Jan., '27.

**Starting Three-Phase Motors with Autotransformers and with Reactors**—C. B. Reed. I-4, W-1820. Vol. XXIV, p. 224. May, '27.

**Induction Motors as Autotransformers**—O. C. Schoenfeld. C-1, D-2, W-2000. Vol. XXIV, p. 381, Aug., '27.

**How Choose a Motor**—A. M. Dudley. (E) W-500. Vol. XXV, p. 117, Mar., '28.

**Air-Gap of Induction Motor**—QB, 2341.

### *Performance*

**Induction Motors on Unbalanced Circuits**—A. M. Dudley. D-3, W-2750. Vol. XXI, p. 339. July, '24.

**Effect of Unbalanced Voltages on the Operation of Induction Motors**—O. C. Schoenfeld. T-2, C-3, D-3, W-2900. Vol. XXII, p. 30, Jan., '25.

**Motor Performance on Reduced Voltage**—A. P. Fugill. T-1, C-3, W-3000. Vol. XXII, p. 316, July, '25.

**Effect of Unbalanced Secondary Conditions on the Operation of Large Induction Motors**—A. F. Kenyon. C-7, D-1, W-2120. Vol. XXII, p. 435, Sept., '25.

**The Effect of the Number of Poles on the Power-Factor of Induction Motors**—F. L. Moon. C-6, I-8, W-2250. Vol. XXIII, p. 428. Aug., '26.

**Induction Motor Starting Torque**—C. A. Scarlott. W-100. Vol. XXIII, p. 582. Nov., '26.

**High-Slip Versus High-Torque Motors—Their Application and Characteristics**—E. F. J. Johns. C-2, W-1600. Vol. XXV, p. 100, Feb., '28.

**The Wound-Rotor Induction Motor—Its Performance and Operation at Reduced Speeds**—R. R. Sheely. C-3, D-1, I-1, W-1550. Vol. XXV, p. 342, July, '28.

**One Cause of Motor Current Unbalance**—C. W. Kincaid. W-400. Vol. XXV, p. 463. Sept., '28.

**Determining Slip**—QB, 2343.

**Power-Factor During Regenerative Braking**—QB, 2402.

**Blowing of Fuse During Motor Starting**—QB, 2414.

**Three-Phase Motors Operated on Single-Phase Supply**—QB, 2443.

**Operation of an Induction Motor as a Generator**—QB, 2467.

**Performance Calculations**—QB, 2484.

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**Horse-Power of Motor**—QB, 2499.

**Starting Torque**—QB, 2509.

**Induction Motor as Phase Converter**—QB, 2530.

**Two-Speed Motor Operation**—QB, 2592.

**Relative Performance of Induction Motor using Different Connections and Applied Frequency**—QB, 2626.

**Full Voltage Starting of 150 Hp Squirrel-Cage Motor**—QB, 2632.

**Secondary Resistance for Induction-Motor Control**—QB, 2650.

**Growling of Induction Motors**—QB, 2667.

**Circulating Currents in Delta**—QB, 2684.

**Effect of Over-Voltage on Losses in Squirrel-Cage Motors**—QB, 2727.

**Unbalanced Voltage with Induction Motor Load**—QB, 2743.

**A Synchronous Phase Modifier**—QB, 2749.

**Dynamic Braking with Different Types of Motors**—QB, 2769.

**Operation with Squirrel-Cage Insulation Destroyed**—QB, 2773.

**Calculation of Motor Efficiency at Reduced Speed**—QB, 2786.

**Operating 25 Cycle Motor at 3000 R.P.M.**—QB, 2798.

**High-Slip versus High-Torque Motors**—QB, 2861.

**A 60 Cycle Wound Rotor Motor on 50 Cycles**—QB, 2872.

### *Testing*

**Testing of Winding**—QB, 2365.

**Unbalanced Phases at No-Load**—QB, 2423.

**Motor-Generator Set for Testing Small Alternating-Current Motors**—QB, 2461.

### *Windings*

**Lap Windings with Unequal Coil Groups**—C. R. Riker and A. M. Dudley. T-5, D-6, W-2900. Vol. XXII, p. 25, Jan., '25.

**Fractional Pitch Windings for Induction Motors**—D. F. Alexander. T-2, C-3, D-5, W-3100. Vol. XXV, p. 77, Feb., '28.

**Stripping Impregnated Motor Windings**—A. C. Roe. W-450. Vol. XXV, p. 521, Oct. '28.

**Effect of Substituting Wooden for Magnetic Wedges**—QB, 2385.

**Changing from Single-Layer to Two-Layer Winding**—QB, 2516.

**Full-Overlapping Versus Half-Overlapping Stator Windings**—QB, 2594.

**Rewinding Induction Motor**—QB, 2618.

**Right and Left Hand Stator Windings**—QB, 2628.

**Winding Induction Motors**—QB, 2630.

**Changing Four Pole Motor to Six Poles**—QB, 2651.

### *Connections*

**Common and Independent Star Connections in Two-Parallel, Star-Connected Stator Windings**—QB, 2354.

**Connections for Squirrel-Cage and Slip-Ring Motors and Salient-Pole Synchronous Motors**—QB, 2699.

**Connecting a Wave Wound Rotor for a Three-Phase Motor**—QB, 2747.

### *Reconnection*

**Reconnecting Induction Motor**—QB, 2325.

**T-Connected Motor**—QB, 2593.

**Reconnection of Induction Motor for Two Speeds**—QB, 2614.

### *Design*

**Induction Motor Characteristics and Curves**—B. G. Lamme. Vols. XXIII, XXIV.

**I—The Simple Induction Motor.** D-1, W-3000. p. 451, Sept., '26.

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**II—Speed-Torque: Current: Power-Factor; Effect of Change in Constants; Maximum Torque; Starting Torque; Frequency.** C-16, W-4000. p. 614, Dec., '26.

**III—The Circle Diagram—Derivation of Relationships.** D.2, W-2000. p. 41, Jan., '27.

**IV—Construction of the Circle Diagram.** D-12, W-5900. p. 132, Mar., '27.

**V and VI—Magnetic Flux Distributions, Magnetomotive Forces and Their Influence on Dynamo Construction.** T-1, C-8, I-23, W-7700. p. 174, Apr.; p. 213, May, '27.

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**Induction Motor Slot Construction**—QB, 2368.

**High-Speed Induction Motors**—QB, 2488.

**Ratio of Turns for Two and Three-Phase Motors**—QB, 2588.

**Effect of Doubling the Speed of an Alternating-Current Motor**—QB, 2620.

**Calculation of Wound-Rotor Current**—QB, 2819.

**Distribution Factor**—QB, 2865.

**Induction Motor Punching Area**—QB, 2806.

### *Wound Rotor*

**Slip in Wound-Rotor Induction Motor Due to Resistance of Leads to Starter**—QB, 2363.

**Replacing of Swedish-Type Rotor Winding by Squirrel-Cage Winding**—QB, 2369.

**Operation of Three Wound-Rotor Induction Motors with a Single Controller**—QB, 2374.

### *Squirrel-Cage*

**Polyphase Motors with Double Squirrel-Cage Windings**—C. W. Kincaid and D. F. Alexander. C-7, I-3, W-3140. Vol. XXIII, p. 15, Jan., '26.

**How to Repair Old Squirrel-Cage Rotors.** W-600. Vol. XXV, p. 519, Oct., '28.

**Effect of Grounded Rotor Bars on Performance**—QB, 2388, 2773.

**Removal of Defective Bar in Squirrel-Cage Winding**—QB, 2619.

**Insulating Squirrel-Cage Rotor Bars**—QB 2777.

### *Single-Phase*

**Winding and Connecting Small Single-Phase Motors**—C. A. M. Weber. D-23, I-9, W-2320. Vol. XXI, p. 377, Aug., '24.

**Characteristics of Single-Phase Motors**—J. O. Walz. C-4, I-5, W-4200. Vol. XXIII, p. 461, Sept., '26.

**Phase Splitters**—QB, 2344.

**Starting Winding**—QB, 2434.

**Dead Points in Starting Two-Pole Split-Phase Motor**—QB. 2624.

**Resistance of Starting and Running Windings**—QB, 2758.

**Failure of Single-Phase Motor to Start**—QB, 2841.

### *Repulsion*

**Repulsion-Induction Motor Trouble**—QB. 2412.

### SERIES MOTORS

**Small Series Alternating-Current Motor**—QB, 2541

**Winding Two-Pole Motor**—QB, 2654.

### FAN MOTORS

**Failure of Ceiling Fan**—QB, 2381.

**Increasing Speed of Fan Motor**—QB, 2475.

### BATTERIES

**High-Speed Dry-Battery-Operated Motor**—QB, 2880.

# TRANSFORMATION

## RECTIFIERS

### Mercury-Arc

**Metal-Tank Mercury-Arc Rectifiers**—F. D. Newbury. (E) W-750. Vol. XXII, p. 570, Dec., '25.

**Mercury Arc Rectifier Characteristics**—E. B. Shand. D-7, I-6, W-5900. Vol. XXIV, p. 486, Oct., '27.

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**High-Voltage Mercury Arc Rectifiers**—L. Smede. C-4, D-1, I-2, W-2100. Vol. XXV, p. 403, Aug., '28.

**Automatic Vacuum Gauges**—L. Smede. C-5, I-6, W-2550. Vol. XXV, p. 437, Sept., '28.

### Electronic

**Battery Charging with Rectigons**—E. W. Breisch. T-1, D-5, I-5, W-3040. Vol. XXI, p. 155, Apr., '24.

**Testing and Operation of Rectigon Rectifiers**—S. B. Kraut. C-5, D-6, I-4, W-3350. Vol. XXI, p. 363, Aug., '24.

**Humming in Rectigon Bulbs**—QB, 2648.

**Direction of Current Flow**—QB, 2717.

**Power-Factor of Rectigon Battery Charges**—QB, 2863.

**Bulb Rectification**—QB, 2878.

## SYNCHRONOUS CONVERTERS

**Flash Guards for 60 Cycle Railway Converters**—R. H. Newton. I-3, W-820. Vol. XXI, p. 105, Mar. '24.

**Operation of Synchronous Converters at Reduced Voltages**—E. B. Shand. T-1, W-2200. Vol. XXI, p. 545, Dec., '24.

**Synchronous Converter Copper Loss**—Reuben Lee and H. L. Hildenbrand. T-1, C-4, I-8, W-1610. Vol. XXIII, p. 110. Mar., '26.

**The Reason for the Auxiliary Commutating Winding on Booster Converters.** W-700. Vol. XXV, p. 108, Feb., '28.

**Conversion Equipment for Mining Substations**—R. E. Powers. I-8, W-3450. Vol. XXV, p. 227, May, '28.

**Short-Circuit Protection for Synchronous Converters.** T-1, W-1000. Vol. XXV, p. 200, Apr., '28.

**Portable Inverted Synchronous Converters.** C-1, I-1, W-600. Vol. XXV, p. 311, June, '28.

**Reactive Factor Meters with Converters.** W-150. Vol. XXV, p. 463, Sept., '28.

**The Development of Enclosures for Synchronous Converters**—R. H. Newton. I-9, W-2700. Vol. XXV, p. 586, Dec., '28.

**Reversing Rotation**—QB, 2444.

**Relative Use of Six-Phase Converters**—QB, 2483.

**Hunting in Small Synchronous Converters**—QB, 2603.

**Effect of Frequency on Starting Characteristics of Synchronous Converters**—QB, 2607.

**Cause of Burnout in Synchronous Converter Winding**—QB, 2609.

**Converters in Parallel**—QB, 2639.

**Frog-Leg Windings**—QB, 2644.

**Reversing Two-Phase Converter** — QB, 2700.

**Paralleling Converters and D-C. Generators**—QB, 2711.

**Synchronous Converters for Battery Charging**—QB, 2728.

**Length of Equalizer**—QB, 2807.

**Variation of Synchronous Converter Direct-Current Voltage by Changing Field Excitation**—QB, 2822.

**Inverting a Synchronous Converter**—QB, 2849.

**Operation with One Transformer Out**—QB, 2876.

## STORAGE BATTERIES

**Direct-Current Generators for Battery Charging**—Jos. A. Elzi. C-3, I-1, W-2710. Vol. XXIII, p. 351, July, '26.

**Storage Batteries in the Hands of the Individual User**—J. H. Tracy. W-3700. Vol. XXIV, p. 128, Mar., '27.

**Charging Batteries with Differential Compound Generator**—QB, 2408.

**Motor-Generator Set for Battery Charging**—QB, 2551.

**Synchronous Converters for Battery Charging**—QB, 2728.

**Charging Radio and Automobile Batteries**—QB, 2739.

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## TRANSFORMERS

### General

**The Magnetic Properties of Silicon Steel in a Large Transformer**—G. H. Cole. C-43, W-4440. Vol. XXI, p. 17, Jan., '24.

**Approximate Methods of Transformer Design**—E. G. Reed. T-1, C-5, I-3, W-3470. Vol. XXIII, p. 567, Nov., '26.

**Transformer Fundamentals**—E. G. Reed, I-3, W-2570. Vol. XXIV, p. 30, Jan., '27.

**Use of Synchronous Condensers with Three-Winding Transformers**—R. C. Bergvall, D-3, W-1700. Vol. XXI, p. 205, May, '24.

**Three-Winding Transformers**—J. F. Peters. C-5, D-19, W-9800. Vol. XXII, p. 12, Jan., '25; p. 71, Feb., '25.

**A Valve for Transformer Radiators**—L. H. Hill. C-1, I-9, W-1200. Vol. XXII, p. 45, Jan., '25.

**A Unity Power-Factor Constant-Current Regulator**—L. Dorfman. D-7, I-1, W-2400. Vol. XXII, p. 86, Feb., '25.

**Distribution Transformers**—E. G. Reed. I-5, W-3400. Vol. XXII, p. 295, June, '25.

**Manufacture of Distribution Transformers**—W. A. Sumner. I-15, W-3700. Vol. XXIV, p. 122, Mar., '27.

**Manufacture of Large Power Transformers**—L. H. Hill. I-29, W-4600. Vol. XXIV, p. 146, Apr., p. 203, May, '27.

**Transformer Voltage Ratio Control Under Load**—L. H. Hill. I-13. W-2600. Vol. XXIII, p. 261, May, '26.

**60 000 Kv-a Transformer Banks Equipped for Change of Ratio under Load**—W. M. Dann. D-2, I-8, W-2870. Vol. XXIII, p. 398, Aug., '26.

**Equipment for Controlling the Voltage Ratio of Transformers under Load**—K. A. Oplinger. I-10, W-2100. Vol. XXIV, p. 164, Apr., '27.

**Control and Relay Equipment for Motor-Operated Transformer Tap Changer**—W. R. Farley. T-3, D-6, I-3, W-3800. Vol. XXIV, p. 438, Sept., '27.

**Transformer Fundamentals**—E. G. Reed. I-3, W-2570. Vol. XXIV, p. 30, Jan., '27.

**Phase-Angle Control Under Load by Means of Transformer Tap-Changing Equipment**—L. H. Hill. D-6, I-2, W-2050. Vol. XXV, p. 183, Apr., '28.

**A New Type of Transformer Tap Changer**—R. M. Field. I-8, W-800. Vol. XXV, p. 555, Nov., '28.

**Forced Air-Blast Equipment for Oil-Immersed Transformers**—L. H. Hill. D-2, I-7, W-1400. Vol. XXV, p. 60, Feb., '28.

**Why Insulated Rivets in Transformer Cores.** W-200. Vol. XXV, p. 109, Feb., '28.

**Why Wavy Strips are Used as Transformer Coil Spacers.** W-200. Vol. XXV, p. 112, Feb., '28.

**The Depth of Flutes in Transformer Cases.** W-300. Vol. XXV, p. 250, May, '28.

**Transformer Taps Come from the Middle and Not the End of the Winding.** W-150. Vol. XXV, p. 520, Oct., '28.

**Fusing Primaries**—QB, 2313.

**Rating and Regulation**—QB, 2367.

**Lagging on Cooling Coil**—QB, 2391.

**Use of Ford Spark Coil as Transformer,**—QB, 2395.

**Constant-Current Transformers**—QB, 2440.

**E. M. F. Formulas for Generator and Transformer**—QB, 2469.

**Construction of Resonance Transformer**—QB, 2473.

**Drying Large High-Voltage Transformers**—QB, 2506.

**Common Bus System for Transformers**—QB, 2615.

**Four-Wire Neutral Current with Single-Phase Secondary Load**—QB, 2633.

**Cleaning Transformer Cooling Coils**—QB, 2659.

**Differential Transformer Protection**—QB, 2827.

**Black versus White Paint for Transformers**—QB, 2862.

### Connections

**Delta-Connected Transformers Loaded at Full and Half Voltage**—E. P. Wimmer. C-2, D-3, W-800. Vol. XXII, p. 66, Feb., '25.

**Dissimilar Transformers in Delta—Vector Solution**—J. B. Gibbs. D-6, W-1200. Vol. XXII, p. 121, Mar., '25.

**How to Obtain Current and Voltage in Phase from Three-Phase, Three-Wire System.** W-200. Vol. XXV, p. 367, July, '28.

**Dissimilar Transformers in Delta**—QB, 2511, 2447.

**Autotransformer Connections**—QB, 2340.

**Half Voltage Taps on Delta**—QB, 2433.

**Single-Phase Load from Three-Phase Bank**—QB, 2435.

**Interconnected Star or Zigzag Connection of Three-Phase Bank**—QB, 2450.

**Grounding Methods and Transformer Connections**—QB, 2457.

**Dissymmetrical Connections**—QB, 2468.

**Phasing Out for Parallel Operation**—QB, 2481.

**Delta Connection of Single-Phase Transformers**—QB, 2523.

**Ground in Three-Phase Secondary on Scott-Connected Transformers**—QB, 2536.

**Taps on High-Tension Transformer**—QB, 2564.

**Differential Protection of Star-Delta Transformer Bank**—QB, 2574.

**Voltage in Delta**—QB, 2653.

**Vector Relations in Delta**—QB, 2698.

**Booster Capacity**—QB, 2703.

**Grounding Midpoints of Delta Bank**—QB, 2734.

**Motor Insulation Test**—QB, 2738.

**Three-Wire Load**—QB, 2740.

**Booster Connections and Size**—QB, 2748.

**Single-Phase Load on Three-Phase Feeder**—QB, 2792.

**N.E.M.A. Rules on Transformer Connections**—QB, 2885.

**Transformers in Parallel**—QB, 2839.

**Angular Displacement of Windings of Double Primary Transformer**—QB, 2847.

**Zig-Zag Transformer for Grounding**—QB, 2851.

**Grounding Transformer Secondary Neutral**—QB, 2858.

**Three-Phase, Four-Wire and Open-Delta Loads**—QB, 2859.

**House Lighting from Power Transformer Banks**—QB, 2864.

#### POLYPHASE TO 1 PHASE

**Single-Phase to Three-Phase**—QB, 2386.

**Spot Welding Transformer on Three-Phase Circuit**—QB, 2757.

**Three-Phase to Single-Phase Transformation**—QB, 2774.

**Transforming from Three-Phase to Single-Phase**—QB, 2803.

#### 3 PHASE TO 2 PHASE

**Taylor Connection for Three-Phase to Two-Phase Transformation**—J. B. Gibbs. C-1, I-5, W-2200. Vol. XXIII, p. 341, July, '26.

**Current Relations in Scott-Connected Autotransformers**—QB, 2380.

**Obtaining Two-Phase Output From Three-Phase Transformer**—QB, 2382.

**Effect of Unbalanced Impedances**—QB, 2390.

**Vector Relations**—QB, 2422.

**Rating of Three-Phase to Two-Phase Transformers**—QB, 2799.

**Autotransformer Phase Transformation**—QB, 2846.

#### OPEN DELTA

**The Open Delta Connection on a Three-Phase Four-Wire System**—J. B. Gibbs. I-5, W-2730. Vol. XXI, p. 36, Jan., '24.

**The Transformer V Connection**—C. G. Veinott. C-1, T-1, D-7, W-1550. Vol. XXV, p. 110, Feb., '28.

**Three-Wire Single-Phase on Open Delta**—QB, 2316.

**V-Connected Transformers on Four-Wire Circuits**—QB, 2357.

**Adding Third Transformer to Open Delta**—QB, 2359.

**Three-Phase Transformers in Open Delta**—QB, 2371.

**Relative Capacity of Open-Delta Connections**—QB, 2454.

**Autotransformers in Open-Delta**—QB, 2556.

**Delta and Open Delta Operation with Unequal Transformers**—QB, 2668.

**Unbalance Produced by Open Delta Transformers**—QB, 2787.

#### PARALLEL

**Two-Winding and Three-Winding Banks in Parallel**—QB, 2393.

**Methods of Fusing Parallel Transformers**—QB, 2397.

**Phasing Out**—QB, 2552.

#### POLARITY

**Transformer Polarity**—QB, 2342.

**Bibliography**—QB, 2431.

**Positive Polarity**—QB, 2442.

**Determination of Polarity**—QB, 2456.

**Connections and Polarity**—QB, 2549.

### Performance

**Loading Transformers on a Temperature Basis**—E. G. Reed and W. A. Sumner. T-3, C-5, W-2060. Vol. XXII, p. 551, Nov., '25.

**Electrostatic Stresses in Transformers under Operating Conditions**—E. G. Reed. T-1, I-10, W-3270. Vol. XXIII, p. 32, Jan., '26.

**Current, Voltage and Flux Relations**—QB, 2315.

**Relative Directions of Secondary E. M. F. with Rising and Falling Voltage in Primary**—QB, 2361.

**40 Cycle Excitation of 60 Cycle Transformer**—QB, 2373.

**Transformer Secondary Action**—QB, 2418.

**Reduction of No-Load Current**—QB, 2420.

**Calculation of Characteristics**—QB, 2429.

**Excitation Losses**—QB, 2441.

**Impedance Rating**—QB, 2464.

**Effect of Ambient Temperature on Capacity**—QB, 2476

**Impedance of Single-Phase Transformer**—QB, 2486.

**Regulation with Leading Power-Factor Load**—QB, 2489.

**Operation below Rated Voltage**—QB, 2498.

**Single-Phase Transformers with Three-Wire Secondaries**—QB, 2514.

**Current and Voltage Relations in Three-Phase Bank**—QB, 2518.

**Heat Run on Single-Phase Transformer**—QB, 2528

**Transformer Switching**—QB, 2532, 2546.

**Load Division in Three-Phase Four-Wire Bank**—QB, 2676.

**Effect of Ambient Temperature on Output**—QB, 2677.

**Rating of Transformers above Sea Level**—QB, 2751.

**Temperatures**—QB, 2776.

**Transformer Temperature Rise**—QB, 2789.

**Cooling Coils and Water for O.I.W.C. Transformer**—QB, 2800.

**Hot Spot Indicators**—QB, 2811.

**Transmission Line Reactance**—QB, 2824.

**Capacity Current**—QB, 2826.

**Transformers in Parallel**—QB, 2828.

**Calculation of Transformer Impedance**—QB, 2843.

### Testing

**Testing Large Power Transformers**—W. J. Harrer and A. Heckman. I-8, W-2400. Vol. XXIV, p. 291, June, '27.

**A Method for Testing Transformers and Meters at Reduced Power-Factors, Using Non-Reactive Loads**—C. G. Veinott. T-1, C-1, I-4, W-2950. Vol. XXV, p. 521, Oct., '28.

**Measuring Ratios**—QB, 2419.

**Testing Constant-Current Transformers**—QB, 2705.

**Testing Transformer**—QB, 2856.

### Instrument

**Metering Combined Single and Three-Phase 110-200-400 Volt Service**—QB, 2590.

**Correction of Ratio Error**—QB, 2838.

**Polarity Markings**—QB, 2852.

#### SERIES

**The Phase Angle of the Current Transformer**—E. G. Reed. C-6, W-1170. Vol. XXII, p. 594, Dec., '25.

**Current Transformer Calculations**—E. G. Reed, C-1, I-3, W-3250. Vol. XXIII, p. 67, Feb., '26.

**Ring Type Current Transformers**—A. M. Wiggins. T-1, C-8, D-2, I-3, W-2400. Vol. XXIV, p. 621, Dec., '27.

**Overloads on Current Transformers.** C-1, I-1, W-200. Vol. XXV, p. 249, May, '28.

**Principles of the Series Transformer**—QB, 2370.

**Voltampere Capacity**—QB, 2389.

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**Magnetization on Short-Circuit—QB, 2462.**

**Taps on Split-Type Current Transformer—** QB, 2470.

**Inverse Operation—QB, 2521.**

**Current Balance Transformers—QB, 2565.**

**Ratio and Phase Angle under Heavy Overloads—QB, 2579.**

**Series and Multiple Connections—QB, 2617.**

**Accuracy on Half-Load—QB, 2652.**

**Opening Secondary—QB, 2673.**

**Current Transformer Errors—QB, 2695.**

**Current Transformer Connections—QB, 2716, 2771.**

**Connections for Control of Induction Voltage Regulators—QB, 2763.**

**Secondary Leads of Current Transformers—QB, 2797.**

**Tests of Current Transformers—QB, 2840.**

*Potential*

**The Permanence of Voltage Transformer Calibration.** W-200. Vol. XXV, p. 200, Apr., '28.

**Fusing Instrument Transformers.** W-150. Vol. XXV, p. 415, Aug., '28.

**Effect of Burden on Accuracy—QB, 2583.**

### Autotransformers

**Some Autotransformer Relations—Reuben** Lee. C-1, D-4, W-1500. Vol. XXIII, p. 563, Nov., '26.

**Induction Motors as Autotransformers—** O. C. Schoenfeld. C-1, D-2, W-2000. Vol. XXIV, p. 381, Aug., '27.

**Equivalent Resistance and Reactance—QB, 2459.**

**Open-Delta—QB, 2556.**

**Auto-Transformer Connections—QB, 2649.**

**Unbalanced Load from Autotransformers—** QB, 2867.

### Reactance Coils

**Abnormal Behavior of Iron-Cored Reactors in Condensive Circuits—H. B. Dwight.** C-1, D-3, W-1220. Vol. XXI, p. 324, July, '24.

**Zero Mutual Inductance Positions of Coils with Parallel Axes—H. P. Dwight and J. P.** Skillen. C-2, W-1000. Vol. XXII, p. 588, Dec., '25.

**"No-Winding" Reactors for Paralleling Transformers and for Secondary Network—** J. S. Hebrew, T-2, C-2, I-11, W-2090, Vol. XXIII, p. 329, June, '26.

**Iron Core Reactors with Air-Gaps—An Approximate Method of Design—A. M. Wig**gins. I-1, W-2560. Vol. XXIV, p. 20, Jan., '27.

**Recent Developments in Current-Limiting Reactors—L. H. Hill. T-1, I-10, W-2400.** Vol. XXV, p. 131, Mar., '28.

**Starting Three-Phase Motors with Autotransformers and with Reactors—C. B. Reed.** I-4, W-1820. Vol. XXIV, p. 224, May, '27.

**Direct-Current Reactors—A. M. Wiggins,** C-7, I-2, W-2500. Vol. XXIV, p. 563, Nov., '27.

**Neutral Grounding Reactor—QB, 2330.**

**Air-Gap—QB, 2479.**

**Percent Reactance of Bus Reactors—QB,** 2622.

### Oil

**A New Portable Oil Testing Set—A. M.** Wiggins. C-1, I-3, W-1150. Vol. XXV, p. 301, June, '28.

**How to Prevent Transformer Oil Syphoning.** I-4, W-400. Vol. XXV, p. 313, June, '28.

**Methods of Filling Transformer with Oil—** QB, 2364.

**Renewal of Transformer Oil—QB, 2495.**

**Contamination of Transformer Oil—QB,** 2820.

### CONDENSERS

**The Application of Static Condensers to High-Frequency Furnaces—R. E. Marbury.** I-6, W-850. Vol. XXI, p. 421, Sept., '24.

**Localized Correction of Power-Factor—R.** E. Marbury. T-1, C-3, D-1, I-8, W-2400. Vol. XXI, p. 583, Dec., '24.

**Static Condensers for the Higher Distribution Voltages—R. A. Lane. I-7, W-2150.** Vol. XXII, p. 68, Feb., '25.

**Filter Condensers—R. E. Marbury. T-1,** D-1, I-3, W-3110. Vol. XXII, p. 351, July, '25.

**Recent Improvements in Static Condensers for Individual Motors—R. E. Marbury. T-1,** C-5, I-5, W-4240. Vol. XXIII, p. 221, May, '26.

**Power-Factor Correction in Steel Mills—E.** F. Rhodes. I-8, W-1090. Vol. XXIII, p. 287, June, '26.

**Conversion of Kv-a Rating to Farads—QB,** 2455.

**P-F Correction in Coal Mines—QB, 2685.**

**Electrolytic Condenser for B-Eliminator Filter Circuit—QB, 2788.**

# TRANSMISSION

## CONDUCTORS and CONTROL

### GENERAL

(See also Theory, p. 5)

**Mechanical Characteristics of Transmission Lines—L. E Imlay. Vol. XXII, 1925.**

**I—Conductor Characteristics—Wind and Ice Loading.** T-7, I-3, W-3950. p 3, Jan. (E) Chas. F. Scott. W-1200, p. 1.

**II and III—Span Formulae and General Methods of Calculation.** T-5, C-2, D-2, I-8, W-5680. p. 53, Feb.; p. 125, Mar.

**IV and V—Insulators.** I-11, W-6670. p. 186, Apr.; p. 225, May.

**VI, VII and VIII—Transmission Towers.** T-1, I-9, W-10 510. p. 356, July; p. 402, Aug.; p. 452, Sept.

**IX—Economics of Transmission Line Design.** T-1, C-3, I-1, W-5000. p. 502, Oct.

**X—Stringing Conductors on Suspension Insulators—Transmission Line Costs.** T-3, C-2, W-2670. p. 562, Nov.

**XI—Construction of Long Spans.** T-1, I-19, W-5020. p. 596, Dec.

**The Economic Balance in Electrical Transmission—Philip Chapin Jones.** T-1, C-1, W-2550. Vol. XXII, p. 9, Jan., '25.

**Short-Circuit Calculation—QB, 2350, 2768.**

**Effect of Ground Wire on Capacity—QB,** 2755.

### Power-Factor

**Power-Factor Correction in Philadelphia—** Chas. J. Russell. T-1, W-1010. Vol. XXI, p. 201, May, '24.

**Localized Correction of Power-Factor—R.** E. Marbury. T-1, C-3, D-1, I-8, W-2400. Vol. XXI, p. 583, Dec., '24.

**Measurement of Power-Factor in Industrial Plants—R. A. Lane. C-2, D-4, I-1, W-**1900. Vol. XXII, p. 391, Aug., '25.

**The Correction of Power-Factor by the Use of Synchronous Motors—P. C. Jones.** C-2, D-1, W-1730. Vol. XXIII, p. 99, Mar., '26.

**Power-Factor Correction in Steel Mills—** E. F. Rhodes. I-8, W-1090. Vol. XXIII, p. 287, June, '26.

**Phase-Angle Control Under Load by Means of Transformer Tap-Changing Equipment—L.** H. Hill. D-6, I-2, W-2050. Vol. XXV, p. 183, Apr., '28.

**Effect of Synchronous Condenser on Line Voltage—QB, 2392.**

**P-F. during Regenerative Braking—QB,** 2402.

**Capacity of Synchronous Motor—QB, 2445.**

**Determination by Polyphase Wattmeter—** QB, 2448.

**P-F. Relations—QB, 2527.**

**P-F. of Industrial Load—QB, 2568, 2732.**

**P-F. Correction in Coal Mines—QB, 2685.**

**Asynchronous Phase Modifier—QB, 2749.**

### SYSTEMS

**Interconnection of Power Systems—A. H.** McIntire. (E) W-900. Vol. XXI, p. 539, Dec., '24.

**Interconnection, Superpower and Electrification—S. Q. Hayes. T-6, I-31, W-19 940.** Vol. XXI, p. 72, Feb., '24; p. 118, Mar., '24; p. 166, Apr., '24; p. 247, May, '24.

**Transmission System of the Southern California Edison Co.—H. A. Barre. I-5, W-**1380. Vol. XXII, p. 257, June, '25.

**Electrical Distribution at Los Angeles—** Carl A. Heinze. I-5, W-4580. Vol. XXII, p. 261, June, '25.

**Electric Distribution Network of the Pacific Gas & Electric Co.—S. J. Lisberger.** I-9, W-4080. Vol. XXII, p. 268, June, '25.

**Hydro-Electric System of Pacific Gas & Electric Co.—J. P. Jollyman. T-1, I-5, W-**2090. Vol. XXII, p. 274, June, '25.

**Hydro-Electric Development in Southern Oregon and Northern California.—P. O. Craw**ford. I-7, W-1760. Vol. XXII, p. 278, June, '25.

**The 4000 Volt Distribution System of the Duquesne Light Co.—Samuel Rosenbach. D-1,** I-11, W-3650. Vol. XXII, p. 289, June, '25.

**Alternating-Current Distribution Networks** —Chas. R. Riker. (E) W-850. Vol. XXII, p. 313, July, '25.

**Evolution of Alternating-Current Secondary Networks—H. Richter. T-1, C-1, I-19,** W-12410. Vol. XXII, p. 320, July, '25.

**Recent Developments in Automatic Network Units—G. G. Grissinger. C-1, D-1, I-2, W-**1850. Vol. XXII, p. 336, July, '25

**The Automatic Network Relay—John S.** Parsons. C-3, I-4, W-4310. Vol. XXII, p. 339, July, '25.

**Motor Performance on Combined Secondary Networks—A. P. Fugill. T-1, C-3, W-8000.** Vol. XXII, p. 316, July, '25.

**Regulators for Network Distribution Systems—E. E. Lehr. D-1, W-1280. Vol. XXII,** p. 344, July, '25.

**Regulators on Network Feeders—C. C.** Hudspeth. D-4, W-1320. Vol. XXII, p. 346, July, '25.

**Alternating-Current Networks—H. Richter.** (E) W-100. Vol. XXV, p. 57, Feb., '28.

**Oil Switches for Distribution Systems—** F. B. Kniskern. D-2, I-9, W-1880. Vol. XXII, p. 348, July, '25.

**A Mechanical Analogy to the Problem of Transmission Stability—S. B. Griscom. I-11,** W-4230. Vol. XXIII, p. 230, May, '26.

**System Stability with Quick-Response Excitation and Voltage Regulators—J. H. Ash**baugh and H. C. Nycum. C-4, I-2, D-1, W-3750. Vol. XXV, p. 504, Oct., '28.

**Problems Arising from the Expansion and Interconnection of Power Systems—F. C.** Hanker. I-5, W-4400. Vol. XXIV, p. 96, Mar., '27.

**Characteristics of Ground Faults on Three-Phase Systems—S. B. Griscom. T-2,** C-4, D-1, I-7, W-3800. Vol. XXIV, p. 151, Apr., '27.

**The Speed Control of a Transmission System—J. P. Jollyman. T-1, C-2, W-1200. Vol.** XXIV, p. 250, June, '27.

**The Interconnection of Power Systems Surrounding the Pittsburgh District—Geo. S.** Humphrey. T-1, I-3, W-5600. Vol. XXIV, p. 251, June, '27.

**Changing a Transmission System to Operate at Double Voltage—W. C. Sontum.** D-1, W-2580. Vol. XXIV, p. 265, June, '27.

**The Relaying Problems of a Typical Large Interconnection—B. M. Jones. C-1, D-1, W-**1100. Vol. XXV, p. 171, Apr., '28.

**Operating Problems of Interconnected Power Systems—Wm. R. Hamilton. C-1, I-6,** W-4400. Vol. XXV, p. 494, Oct., '28.

**Cause of High Potential Accompanying Short-Circuit on D. C. Line—QB, 2351.**

**Solution of Simple Network—QB, 2446.**

**Natural Frequency of Transmission Circuit** —QB, 2471.

**Effect of Grounded Secondary on Generator with Grounded Neutral—QB, 2589.**

**Faults on Transmission Lines—QB, 2693.**

**Transmission System Speed Control—QB,** 2804.

**Distribution Scheme—QB, 2810.**

**Reduction of Interference from Third Harmonic in an Ungrounded Star—Star System** —QB, 2812.

**Small Power Line Problems—QB, 2815.**

**Vector Diagram for Single-Phase Load—** QB, 2816.

**Transmitting Unbalanced Single-Phase Loads—QB, 2823.**

**Short-Circuit Current—QB, 2830.**

**Transmission Problems—QB, 2868.**

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## Phasing

**The Phase Rotation Indicator**—H. L. Hildenbrand. I-5, W-1000. Vol. XXIII. p. 57, Feb., '26.

**Determining Phase Rotation of a Three-Phase System**—QB, 2355.

**Phasing Out Transformer Banks for Parallel Operation**—QB, 2481.

**Phase Rotation**—QB, 2539.

**Line Drop Compensation for Unbalanced Load**—QB, 2634.

## LINES

**The Operation of 220 000 Volt Transmission Lines**—A. W. Copley. D-2, I-1, W-1850. Vol. XXI, p. 202, May, '24.

**Analytical Solution of Networks**—R. D. Evans. D-23, W-10 170. Vol. XXI, p. 149, Apr., 24; p. 207, May, '24.

**The Application of Decrement Factors in Short-Circuit Studies**—W. R. Woodward. T-5, C-1, D-3, W-2390. Vol. XXI, p. 213, May, '24.

**Over Voltages on Transmission Lines During Generator Runaway**—H. R. Stewart. T-1, C-10, D-2, W-5000. Vol. XXIV, p. 607, Dec., '27.

**Calculation of Sags in a Transmission Line with a Broken Conductor**—J. P. Den Hartog. T-2, I-5, W-1700. Vol. XXV, p. 24, Jan., '28.

**Some Transmission Line Fundamentals**—C. A. Boddie. C-1, I-11, W-7900. Vol. XXV, p. 32, Jan.; p. 82, Feb., '28.

**Phasing Out Transmission Lines**—QB, 2319.

**Parallel Operation of Dissimilar Transmission Lines**—QB, 2387.

**Compensating for the Inductive Component of Line Drop**—QB, 2569.

**Testing a Repaired Transmission Line Fault**—QB, 2790.

**Transmission Line No-Load Losses**—QB, 2879.

## Underground

**Calculation of the Electrical Problems of Transmission by Underground Cables**—Donald M. Simons. T-4, C-2, D-1, W-16840. Vol. XXII, p. 366, Aug., '25.
(E) Chas. R. Riker W-800, p. 365.

**Calculation of Current-Carrying Capacity of Type H Cable**—D. M. Simons. T-1, I-3, W-3870. Vol. XXIII, p. 59, Feb., '26.

**Losses in Grounded Sheaths of Single-Conductor Cables**—H. B. Dwight. I-2, W-4100. Vol. XXI, p. 62, Feb., '24.
(E) D. M. Simons. W-1200, p. 51.

**A High-Tension Bridge for Measurement of Dielectric Losses in Cables**—R. W. Atkinson. D-6, I-1, W-7780. Vol. XXII, p. 58, Feb., '25.
(E) Donald M. Simons. W-450, p. 51

**Inductive Losses In Three-Conductor Type H Cables**—Donald M. Simons. T-1, I-1, W-1380. Vol. XXIV, p. 115, Mar., '27.

**Progress in Underground Distribution**—C. H. Shaw. (E) W-800. Vol. XXIV, p. 249, June, '27.

**Temperature Rise of Cables**—QB, 2320.

**Losses in Single-Conductor Lead Sheath Cables**—QB, 2352.

**Capacity to Neutral for Lead Sheathed Cable**—QB, 2398.

**Static Shields for Lead Covered Cables**—QB, 2417.

**Breakdown Test on Lead-Covered Cables**—QB, 2612.

**Formation of Ozone on High Voltage Cables**—QB, 2655.

**Short Circuit Due to Cable Failures in Underground Systems**—QB, 2664.

**Carrying Capacity of Varnished Cambric and Rubber Covered Cable**—QB, 2709.

**Overload Capacity of Cable**—QB, 2742.

**Cable Testing**—QB, 2860.

**Current in Underground Cable Sheath**—QB, 2877.

## Overhead

**Hollowspun Concrete Poles for Trolley, Telegraph, Telephone and Power Lines**—L. A. S. Wood. C-1, I-8, W-2300. Vol. XXIV, p. 603, Dec., '27.

**Clearances between Conductors and to Ground**—QB, 2347.

**Wave Length of Transmission Line**—QB, 2404.

**Transpositions**—QB, 2542.

**Measurements of Sag**—QB, 2584.

**Virtual Co-efficient of Aluminum Cable, Steel Reinforced**—QB, 2671.

**Charging Currents**—QB, 2686.

**Cable Transposition**—QB, 2780.

**Reactance of Widely Spaced Conductors**—QB, 2857.

### GROUNDING

**Protective Grounds**—V. E. Johnson. C-1, I-10, W-6150. Vol. XXV, p. 381, Aug.; p. 447 Sept., '28.

**Effect of Ground on Delta System**—QB, 2326.

**Neutral Grounding Reactor**—QB, 2330.

**Transformer for Grounding Bus-Bars**—QB, 2332.

**Ground on Both Phases of Two-Phase System**—QB, 2334.

**Grounding Methods and Transformer Connections**—QB, 2457.

**Effect of Charcoal around Ground Plates**—QB, 2524.

**Corrosion at Contact of Dissimilar Metals in Moist Soil**—QB, 2538.

**Grounding Generators and Transformers**—QB, 2691.

**Grounds on Transmission Lines**—QB, 2693.

**Grounding Generator Neutral**—QB, 2721.

**Grounding Midpoints of Delta Transformers Bank**—QB, 2734.

**Peculiar Behavior of Ground Detector**—QB, 2844.

**Ground Detectors**—QB, 2834.

**Grounding Transformer Secondary Neutral**—QB, 2858.

## Conductors

**The Resistance of Electrical Connections**—G. E. Luke. T-1, C-4, I-3, W-2640. Vol. XXI, p. 66. Feb., '24.

**The Contact Resistance of Large Conductors**—Arne R. Enger. C-6, W-2060. Vol. XXI, p. 316, July, '24.

**Alternating-Current Conductivity of Iron Pipe**—H. B. Dwight. T-1, C-5, W-1720. Vol. XXIII, p. 295, June, '26.

**Current Carrying Capacity of Bare Cables**—W. M. Woll and J. A. Gable. C-6, W-1320. Vol. XXIII, p. 557, Nov., '26.

**Heater Cord Standards**—Frank Thornton, Jr. (E) W-500. Vol. XXV, p. 265, June, '28.

**Trolley Wire for Mine Service**—H. N. Richards. I-3, W-900. Vol. XXV, p. 237, May, '28.

**Cable Lead Terminals and Connectors**—ROD, XXIV, p. 231.

**Motor Cable Leads**—ROD, XXIV, p. 410.

**Effect of Stranding on Electrical Properties**—QB, 2406.

**Crystallization of Leads**—QB, 2451.

**Impedance of Single Wire In Conduit**—QB, 2463.

**Calculation of Voltage Drop on Bus**—QB, 2480.

**Corrosion of High-Voltage Copper Conductor at Bushings**—QB, 2625.

**Temperature of Bus Bars in a Tunnel**—QB, 2735.

## SWITCHBOARDS

### General

**Automatic Operation of Electrical Equipment**—R. J. Wensley. (E) W-800. Vol. XXIII. p. 149, Apr., '26.

**Methods of Automatically Synchronizing Water-Wheel Generators in Automatic Hydro-Electric-Generating Stations**—M. E. Reagan. D-1, I-5, W-5520. Vol. XXIII, p. 172, Apr., '26.

**Automatic Control of Hydro-Electric Plants on the Peshtigo River**—A. G. Carson and E. D. Lilja. I-5, W-2440. Vol. XXIII, p. 168 Apr., '26.

**Full Automatic Phase Modifier Station**—Northwestern Electric Company, Portland, Oregon—E. F. Pearson and Tom Perry. I-4, W-1460. Vol. XXIII, p. 154, Apr., '26.

**Automatic Reclosing Equipment for Alternating-Current Feeders**—A. J. A. Peterson and R. F. Frenger. D-8, I-7, W-8800. Vol. XXIII, p. 179, Apr., '26.

**Protective Equipment for Direct-Current Networks**—M. M. Ewell. I-7, W-1860. Vol. XXIII, p. 227, May, '26.

**Supervisory Control**—J. L. McCoy and W. R. Swoish. T-2, C-1, D-2, I-7, W-3810. Vol. XXIII, p. 311, June, '26

**Power Station Control Boards in the Toronto Power Station and Boardman Substation of the Ohio River Edison Co.**—Ernst Zeuthen. D-3, I-4, W-3300. Vol. XXIII, p. 4, Jan., '26.

**Dead-Front, Steel-Panel Switchboards**—W. H. Schramm. I-5, W-1070. Vol. XXIII. p. 247, May, '26.

**"No-Winding" Reactors for Paralleling Transformers and for Secondary Networks**—J. S. Hebrew. T-2, C-2, I-11, W-2090. Vol. XXIII, p. 329, June, '26.

**Short-Circuit Calculating Table of the Variable Resistor Unit, Direct-Current Type**—I. T. Monseth and R. De Camp. T-3, D-3, I-5, W-4350. Vol. XXIII, p. 299, June, '26.

**All Steel Mounting of Supervisory Control Equipment**—J. L. McCoy. I-6, W-2200. Vol. XXIV, p. 296, June, '27.

**Stresses in Bus Supports**—R. Tanberg T-3, C-10, I-15, W-5900. Vol. XXIV, p. 517, Oct., '27.

**Load Dispatcher's Board of the Georgia Power Co.**—W. B. Flynn. I-4, W-1300. Vol. XXIV, p. 579, Dec., '27.

**Recent Developments in Automatic Network Protectors**—G. G. Grissinger. I-3, D-4, W-2500. Vol. XXIV, p. 583, Dec., '27.

**Recent Developments in Automatic Network Relays**—John S. Parsons. C-5, D-2, I-2, W-3100. Vol. XXIV, p. 587, Dec., '27.

**The Development of the Televox**—R. J. Wensley. I-1, W-1800. Vol. XXIV, p. 601, Dec., '27.

**The Use of Steel in Switchboard Design**—T. A. Kenny. I-4, W-1370. Vol. XXV, p. 613, Dec., '28.

**The Why of the Equalizer.** W-400. Vol. XXV, p. 46, Jan., '28.

**How to Plug Holes in Panels.** W-300. Vol. XXV, p. 200, Apr., '28.

**How to Refinish or Clean Switchboard Panels.** W-150. Vol. XXV, p. 367, July, '28.

**Transformer for Grounding Bus-Bars**—QB, 2332.

**Spacing of Bus Supports**—QB, 2356.

**Short-Circuit Currents and Mechanical Forces on Bus-Bars**—QB, 2409.

**Omission of Oil Switches**—QB, 2428.

**Calculation of Voltage Drop on Bus**—QB, 2480.

**Operation of Other Equipment from Oil-Switch Control Battery**—QB, 2604.

**Common Bus System for Transformers**—QB, 2615.

**Percent Reactance of Bus Reactors**—QB, 2622.

**Generator Ground Currents**—QB, 2657.

**Temperature of Bus-Bars in a Tunnel**—QB, 2735.

**Bus Bar Stresses**—QB, 2835.

## Interrupting Devices

### SWITCHES

**High-Power Laboratory for Testing Oil Circuit Breakers**—W. R. Woodward. D-1, I-9, W-2740. Vol. XXIII. p. 102. Mar., '26.

**Outs for Overhead Distribution**—H. J. Crabbs. T-2, I-10, W-2520. Vol. XXII, p. 305, June, '25.

**Truck-Type Switching Equipment for Industrial Plants and Steel Mills**—M. H. Hobbs. D-1, I-5, W-1470. Vol. XXIII. p. 319, June, '26.

**Analysis of Oil Circuit Breaker Requirements for Large Steel Plants**—M. J. Wohlgemuth. D-7, W-1850. Vol. XXI, p. 409, Sept., '24.

**Recent Developments in Switching Equipments for Industrial Plant Electrification**—M. J. Wohlgemuth. I-4, W-750. Vol. XXIII, p. 298, June, '26.

**Latches and Operating Sticks for Disconnecting Switches**—H. J. Crabbs. I-9, W-1500. Vol. XXI, p. 478, Oct., '24.

**Insulating Oils for Oil Circuit Breakers**—Dean Harvey. C-1, I-6, W-4900. Vol. XXI, p. 573, Dec., '24.

**Switch Oil Requirements and Characteristics**—C. J. Rodman T-1, C-4, D-1, W-2960. Vol. XXII, p. 216, May, '25.

**Disconnecting Switches and Primary Cut-Outs for Overhead Distribution**—H. J Crabbs. T-2, I-10, W-2520. Vol. XXII, p. 305, June, '25

**Oil Switches for Distribution Systems**—F. B. Kniskern. D-2, I-9, W-1880. Vol. XXII, p. 348, July, '25.

**High-Power Direct-Current Tests**—H. M. Wilcox. T-1, C-6, D-1, I-3, W-4480. Vol. XXIII, p. 524, Oct., '26.

**Pneumatic Control of Direct-Current Power Equipment**—L. D. Bale. D-1, I-1, W-2400. Vol. XXIII, p. 530, Oct., '26.

**Switching Equipment for Isolated Loads**—M. H. Hobbs. D-4, I-11, W-3800. Vol. XXIV, p. 258, June, '27.

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**Automatic Switching Control for Mercury Arc Rectifiers**—M. E. Reagan. D-1, I-1, W-2400. Vol. XXIV, p. 496, Oct., '27.

**Switching-Surge Investigations with the Klydonograph**—P. H. McAuley. T-5, D-1, I-2, W-2340. Vol. XXIV, p. 9, Jan., '27.

**The Calculation of Current Value of Asymmetrical, Sinusoidal Waves**—R. C. Van Sickle. T-1, C-6, W-2600. Vol. XXIV, p. 451, Sept., '27.

(E) R. D. Evans. W-600. p. 416.

**A Laboratory for Testing the Interrupting Capacities of Direct-Current Circuit Breakers**—W. R. Woodward. I-5, W-1500. Vol. XXIV, p. 502. Oct., '27.

**Contact Resistance of Electric Switching Apparatus**—W. Schaelchlin. C-5, D-8, W-4400. Vol. XXV, p. 386, Aug., '28.

**Influence of Flux on Circuit-Breaker Top Design**—F. Bice Johnson. I-1, W-700. Vol. XXV, p. 312, June, '28.

**Methods of Applying Relays to Circuit-Breakers.** W-950. Vol. XXV, p. 415, Aug., '28.

**Fundamentals of Magnetic Blowout Structures**—L. G. Riley. C-1, I-14, W-3450. Vol. XXV, p. 485, Oct.; p. 553, Nov., '28.

**How to Select Oil Circuit Breakers—F. B.** Kniskern. I-1, W-350. Vol. XXV, p. 569, Nov., '28.

**Surge Voltages Produced by Direct-Current, Air, Circuit Interrupters**—Leon R. Ludwig. C-5, D-1, I-1, W-2380. Vol. XXV, p. 604, Dec., '28.

**Outdoor Trucks and Housings.** I-2, W-250. Vol. XXV, p. 368, July, '28.

**How to Care for Circuit Breaker Contacts.** W-600. Vol. XXV, p. 568, Nov., '28.

**Simplified Theory of Magnetic Blow-Out**—ROD, XXII, p. 456.

**Grounding Operating Lever of High-Tension Switch**—QB, 2317.

**Carbon Tetrachloride**—QB, 2322.

**Transformer Switching**—QB, 2532.

**National Code Rules in Placing Knife Switches**—QB, 2701.

**Locomotive and Substation Circuit Breakers**—QB, 2714.

**Simultaneous Opening of Circuit Breaker Contacts**—QB, 2770.

**Part of Wave on Which Circuit Breakers Open Circuit**—QB, 2873.

### FUSES

**Fusing Transformer Primaries**—QB, 2313

**Blowing of Fuses**—QB, 2881.

## Protective

**Lightning Protection of Distribution Systems**—A. L. Atherton. C-1, I-2, W-2980 Vol. XXII, p. 301, June, '25.

**Choke Coil Terminals**—L. R. Golladay, W-150. Vol. XXIII, p. 112, Mar., '26.

**Lightning and its Effects on Transmission Lines**—J. H. Cox. T-2, C-4, I-5, W-5700. Vol. XXIV, p. 364, Aug., '27.

**Lightning Arresters for Supervisory Control Systems**—Edward Beck. D-1, I-2, W-1000. Vol. XXIV, p. 388, Aug., '27.

**220 Kv Lightning Arresters**—A. L. Atherton. C-10, I-9, W-6350. Vol. XXV, p. 118. Mar., '28.

**A Theory of Lightning**—Charles LeG. Fortescue. T-1, C-3, I-2, W-6400. Vol. XXV, p. 223, May; p. 291, June, '28.

**Protective Grounds**—V. E. Johnson. C-1, I-10, W-6150. Vol. XXV, p. 381, Aug.; p. 447, Sept., '28.

**Relative Frequency of Voltage Surges Induced by Charged Clouds**—H. L. Wallau. C-3, W-1800. Vol. XXV, p. 374, Aug., '28.

**Apparatus Used in the Investigation of Lightning Phenomena**—Edward Beck. I-9, W-2440. Vol. XXV, p. 591, Dec., '28.

**Choke Coil Effect of Grounded Conduit**—QB, 2337.

**Protection of Series Incandescent Street Lighting Circuits**—QB, 2358.

**Current Limiting Reactors and Choke Coils** QB, 2437.

**Charging Electrolytic Lightning Arresters**—QB, 2496.

**Protection against High-Voltage due to Open Circuit in Alternator Field**—QB, 2543.

**Protection and Metering for Three, Three-Phase Transformers**—QB, 2556.

## Synchronizing Schemes

**Methods of Automatically Synchronizing Water-Wheel Generators**—M. E. Reagan. D-1, I-5, W-5500. Vol. XXIII, p. 172, Apr., '26.

**A New Automatic Synchronizer**—F. H. Gulliksen and H. C. Nycum. C-6, D-3, I-4, W-4100. Vol. XXV, p. 295, June, '28.

**Synchronizing**—QB, 2424.

**Synchronizing Generators**—QB, 2600.

**Operation of Differential Relays when Generators are Synchronized**—QB, 2759.

# REGULATION AND CONTROL

## Regulators

### GENERATOR

**The Extended Broad-Range Voltage Regulator**—J. H. Ashbaugh. D-2, I-2, W-2180. Vol. XXII, p. 559, Nov., '25.

**Operation of Extended-Broad-Range Regulators**—QB, 2517.

**Stability of Direct-Current Generators at Low Voltages and When Used with Voltage Regulators**—C. Lynn, C-4, D-1, I-1, W-3940. Vol. XXI, p. 304, July, '24.

**Compensating for Voltage Drop with Automatic Voltage Regulators**—J. H. Ashbaugh. D-9, W-2700. Vol. XXIII, p. 243, May, '26.

**Line Drop Compensation**—QB, 2674.

**Protection from Overvoltage Due to Voltage Regulators**—J. H. Ashbaugh, D-3, I-2, W-1100. Vol. XXIV, p. 551, Nov., '27.

**Adjustment of Short-Circuit Protective Device on Generator Voltage Regulator**—QB, 2520.

**Parallel Operation of Exciters Controlled by Individual Generator Voltage Regulators**—QB, 2525.

### INDUCTION

**A Unity Power-Factor Constant-Current** Regulator—L. Dorfman, D-7, I-1, W-2400. Vol. XXII, p. 86, Feb., '25.

**Regulators for Network Distribution Systems**—E. E. Lehr. D-1, W-1280. Vol. XXII, p. 344, July, '25.

**Regulators on Network Feeders**—C. C. Hudspeth. D-4, W-1320. Vol. XXII, p. 346, July, '25.

**The Insulation and Winding of Induction Regulators**—R. E. Dawe. D-1, I-11, W-3300. Vol. XXIV, p. 393, Aug., '27.

**The Step Induction Regulator for Transformer Voltage Control**—R. M. Field. C-1, D-2, I-5, W-1450. Vol. XXV, p. 351, July, '28.

**The Development of the Feeder Voltage Regulator**—E. R. Wolfert. D-1, I-11, W-4300. Vol. XXV, p. 441, Sept., '28.

**Selection and Application of Induction Voltage Regulators**—L. G. Tubbs. D-8, I-4, W-3150. Vol. XXV, p. 529, Nov., '28.

**Two Regulators Have Same Current Capacity as Three.** W-350. Vol. XXV, p. 367, July, '28.

**How to Disconnect Induction Regulators.** W-400. Vol. XXV, p. 463, Sept., '28.

**Induction Regulator Magnetization**—QB, 2345.

**Three-Phase Induction Voltage Regulator**—QB, 2507.

**Feeder Regulators in Parallel**—QB, 2645.

**Connecting for Control of Induction Voltage Regulators**—QB, 2763.

**Connecting Primary Coils of Induction Voltage Regulators**—QB, 2772.

**The Compensator Winding on Induction Regulator**—QB, 2850.

### SPEED

**Speed Regulator for Single Motor Drive**—J. H. Ashbaugh. D-3, I-4, W-2200. Vol. XXI, p. 390, Aug., '24.

# CONTROLLERS

**Controller Study for Colleges**—J. H. Belknap. (E) W-650. Vol. XXIII, p. 442. Sept., '26.

### INDUSTRIAL

**How to Make Controller Diagrams**—H. D. James. D-6, I-2, W-2500. Vol. XXI, p. 523, Nov., '24.

**The Control of Synchronous Motors**—H. D. James and J. H. Graybill. D-2, I-2, W-3480. Vol. XXI, p. 335, July, '24.

**The Adaptation of Formed Steel to Motor Control Apparatus**—C. H. Hodgkins. I-11, W-1720. Vol. XXI, p. 80, Jan., '24.

**Control of Electric Motors on Circuits with Fluctuating Voltage**—A. L. Harvey. W-1000. Vol. XXII, p. 128, Mar., '25.

**Automatic Control for Synchronous Condensers**—C. C. Levy. D-1, I-5, W-2740. Vol. XXIII, p. 150, Apr., '26.

**Control for Direct-Current Industrial Motors**—R. T. Kintzing. .W-3000. Vol. XXIV, p. 23, Jan., '27.

**Starting Three-Phase Motors with Autotransformers and with Reactors**—C. B. Reed, I-4, W-1820. Vol. XXIV, p. 224, May, '27.

**Motor Control Developments**—H. D. James. (E) W-1700. Vol. XXIV, p. 417, Sept., '27.

**College Laboratory Controllers—The Unit Panels**—Reuben Lee. T-1, D-2, W-1200. Vol. XXIV, p. 162, Apr., '27.

**I—D-C. Controllers with Counter E. m. f. Acceleration.** T-1, D-1, I-4, W-3200. p. 207, May, '27.

**II—D-C. Controllers: Current Limit Acceleration.** T-2, D-2, I-3, W-2000. p. 284, June, '27.

**III—D-C. Controllers for Dynamic Braking and Reversing Service.** D-5, I-4, W-2900. p. 352, July' '27.

**IV—A-C. Controllers for Squirrel-Cage Motors**—T-2, D-2, I-4, W-2400. p. 390, Aug., '27.

**V—A-C. Controllers for Wound-Rotor Motors.** T-2, C-1, D-2, I-2, W-2400. p. 459, Sept., '27.

**VI—Controllers for Synchronous Motors.** T-2, D-3, I-2, W-2300. p. 513, Oct., '27.

**VII—General Considerations.** T-1, C-1, I-2, W-2900. p. 566, Nov., '27.

**Magnetic Control for Synchronous Motors**—D. E. Inman. D-3, I-7, W-4050. Vol. XXV, p. 431, Sept., '28.

**Bimetal: The Temperature Sentinel**—H. E. Cobb. I-8, W-2750. Vol. XXV, p. 288, June, '28.

**A Thermal Accelerating Relay**—H. E. Cobb. C-1, D-1, I-6, W-1750. Vol. XXV, p. 345, July, '28.

**Inductive Time Limit Control**—W. G. Cook. C-3, D-1, I-9, W-4050. Vol. XXV, p. 327, July, '28.

**Connections for No-Voltage Release Coil on Direct-Current Motor Starter**—QB, 2372.

**Operation of Three Wound-Rotor Induction Motors with a Single Controller**—QB, 2374.

**Secondary Resistance for Induction-Motor Control**—QB, 2650.

**Autostarter on Star or Delta-Connected Motor**—QB, 2729.

### SPECIFIC APPLICATIONS

**Electrical Control Insures Safe Operation of Large Bascule BRIDGE.** I-1, W-300. Vol. XXIV, p. 516, Oct., '27.

**Speed Regulating Controllers for Sectional PAPER MACHINE DRIVES**—R. T. Kintzing. C-1, D-1, I-3, W-4450. Vol. XXIII, p. 163, Apr., '26.

**The Master "Mind" of the Holland TUNNEL**—J. P. Maxwell. D-2, I-8, W-4200. Vol. XXV, p. 17, Jan., '28.

**Conductor Size for Controllers of Induction Motors**—QB, 2635.

### RAILWAY

**Railway Control Protective Systems**—L. G. Riley. D-4, I-3, W-2090. Vol. XXIV, p. 33, Jan., '27.

**The Line Switch as an Adjunct in the Reduction of Maintenance of Main Circuit Controllers**—ROD, XXI, p. 254.

**Inspection and Upkeep of Drum Type Controllers**—ROD, XXV, p. 368.

## Rheostats

**Motor Field Rheostat Design**—Reuben Lee. T-1, C-2, D-1, W-1600. Vol. XXV, p. 616, Dec., '28.

**Standardizing Railway Car Resistors**—ROD, XXII, p. 565.

**Size of Field Rheostat for Shunt Generator**—QB, 2505.

**Power Taken by Delta and Star Connections of Three-Phase Load Rheostat**—QB, 2513.

**Rheostat for Testing Purposes**—QB, 2610.

**Vibration of Control Resistor Bank**—QB, 2643.

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# UTILIZATION

## General

**Application Engineering**—H. W. Cope, (E) W-2080. Vol. XXIII, p. 442, Sept., '26.

**Power-Factor Rate Clauses** — H. B. Dwight. T-3, W-3200. Vol. XXV, p. 14, Jan., '28.

**Heat Radiation from Motor**—QB, 2760.

## ELECTROCHEMISTRY

**Electric Power for Chemical Plants**—J. L. McK. Yardley. T-6, I-4, W-9800. Vol. XXIII, p. 113, Mar., '26.

**Electrodeposition of Copper by Rectified Current**—QB, 2449.

**Electroplating**—QB, 2647.

## LIGHTING

**Better Home Lighting Activity**—J. E. Davidson. (E) W-550. Vol. XXI, p. 192, May, '24.

**Good Light—An Oil for Human Machines**—Samuel G. Hibben. (E) W-1100. Vol. XXII, p. 569, Dec., '25.

**Progress in Industrial Lighting**—J. F. Becker. (E) W-450. Vol. XXIII, p. 207, May, '26.

**Cleaning and Maintenance—A Remedy for Lighting Maladies**—R. L. Zahour. T-1, C-1, I-4, W-1540. Vol. XXIII, p. 259, May, '26.

**Making Electric Railway Cars More Attractive by Modern Illumination**—R. W. Cost. T-1, C-1, I-9, W-2700. Vol. XXIV, p. 219, May, '27.

### STREET

**Advantages of Highway Lighting**—F. M. Reast. I-3, W-960. Vol. XXII, p. 543, Nov., '25.

**Good Lighting Pays**—G. A. Sawin (E) W-650. Vol. XXIV, p. 53, Feb., '27.

**Appraisal of Street Lighting**—L. A. S. Wood. T-2, W-1250. Vol. XXIV, p. 55, Feb., '27.

**Application of Remote Control to Modern Street Lighting**—D. E. Westcott. W-1360. Vol. XXIV, p. 56, Feb., '27.

**Lumens Effective on a Street Surface With Directional Control of Light**—H. E. Lippman. T-1, C-1, D-4, I-1, W-1750. Vol. XXIV, p. 58, Feb., '27.

**An Opportunity for Aggressive Sales Effort**—Robert J. Malcolmson. I-2, W-1200. Vol. XXIV, p. 61, Feb., '27.

**Planning Ahead for Street Lighting**—C. J. Stahl. I-1, W-1350. Vol. XXIV, p. 63, Feb., '27.

**$8,000,000 for Light Installation for St. Louis**—J. C. Hall. T-5, W-1540. Vol. XXIV, p. 65, Feb., '27.

**Financing Street Lighting Systems**—C. H. Shepherd. W-1740. Vol. XXIV, p. 67, Feb., '27.

**Directional Control of Light for Street Illumination**—T. W. Rolph. I-9, W-1840. Vol. XXIV, p. 69, Feb., '27.

**Uniform Illumination for Streets**—H. H. Ashinger. T-1, C-4, I-5, W-1110. Vol. XXIV, p. 77, Feb., '27.

**Resonant Control for Street Lights**—C. A. Boddie. C-5, D-4, I-3, W-3260. Vol. XXIV, p. 72, Feb., '27.

**Lighting the Holland Tunnel**—D. W. Atwater. C-1, I-8, W-3300. Vol. XXIV, p. 347, July, '27.

**A Comparison of Street Light Control Methods**—L. W. Guin. W-2000. Vol. XXIV, p. 444, Sept., '27.

**Low-Voltage Cutouts for Series Street-Lighting Transformers**—E. J. Haverstick. C-7, I-1, W-1450. Vol. XXV, p. 340, July, '28.

**Resonant Control for Street Lights**—QB, 2761.

## POWER

### General

**Cost Reductions by Labor-Saving Devices**—G. E. Stoltz. C-5, W-750. Vol. XXV, p. 217, May, '28.

**Serving the Isolated Load**—M. H. Hobbs. D-4, I-11, W-3800. Vol. XXIV, p. 258, June, '27.

**The Industrial Synchronous Motor**—C. D. Kester. (E) W-1200. Vol. XXIV, p. 531, Nov., '27.

**How Choose a Motor**—A. M. Dudley. (E) W-500. Vol. XXV, p. 117, Mar., '28.

**Operation of Direct-Current Motors in Parallel and Series with Different Types of Load**—C. T. Pearce. C-6, W-3750. Vol. XXV, p. 581, Dec., '28.

**Power Salesmanship**—QB, 2421.

**Changing from 2200 to 4000-volt Service**—QB, 2688.

### SPECIFIC APPLICATIONS OF MOTORS

*(Arranged Alphabetically)*

**Load from AIR COMPRESSOR**—QB, 2605

**BRICK Works Electrification**—QB, 2432.

**Electrically-Operated Movable Railroad and Highway BRIDGES**—H. H. Johnston. D-1, I-5, W-3420. Vol. XXIII, p. 385, July, '26.

**Dual-Frequency CALENDER Drive**—S. G. Nottage. C-1, I-3, W-1750. Vol. XXV, p. 500, Oct., '28.

**Electric Power for CHEMICAL Plants**—J. L. McK. Yardley. T-6, I-4, W-9800. Vol. XXIII, p. 113, Mar., '26.

**P-F Correction in COAL MINE**—QB, 2685.

**Modern Practice of Handling Coal In Bulk at COAL PIERS**—Jas. W. Speer. T-1, I-11, W-3130. Vol. XXI, p. 260, June, '24.

**Electric Quencher Locomotives for By-Product COKE Plants**—H. H. Johnston. I-4, W-2500. Vol. XXI, p. 517, Nov., '24.

**Traveling CRANES for Handling Freight Cars in Railway Terminal Yards**—H. B. Dwight. I-3, W-2300. Vol. XXIII, p. 448, Sept., '26.

**All-Electric Sea-Going Hopper DREDGES**—H. C. Coleman. T-1, D-1, I-7, W-2400. Vol. XXI, p. 438, Sept., '24.

**Electrical Equipment for a 30-Inch Diesel-Electric Pipe-Line DREDGE**—R. W. McNeill. T-2, D-1, I-7, W-2880. Vol. XXIII, p. 403, Aug., '26.

### ELECTRIC ELEVATOR PRACTICE

**I—Classification—Power Requirements**—E. M. Bouton. I-7, W-4500. Vol. XXIII, p. 52, Feb., '26.

(E) H. D. James. W-500, p. 51.

**II—Slow and Medium Speed Elevators**—E. M. Bouton. C-1, I-10, W-4020. Vol. XXIII, p. 125, Mar., '26.

**III—High-Speed Passenger Elevators**—E. M. Bouton. C-7, W-4200. Vol. XXIII, p. 156, Apr., '26.

**IV—Controllers for High-Speed Elevators**—W. F. Eames. C-1, D-2, I-5, W-3780. Vol. XXIII, p. 253, May, '26.

**V—Direct-Current Elevator Motors**—W. R. Harding. I-12, W-2560. Vol. XXIII, p. 322, June, '26.

**VI—Mechanical Equipment and Safety Devices**—E. M. Bouton. C-1, I-11, W-3370. Vol. XXIII, p. 379, July, '26.

**VII—Signals and Dispatching Systems**—E. M. Bouton. W-2800. Vol. XXIII, p. 432, Aug., '26.

**VIII—Installation Tests and Maintenance of Electrical Apparatus**—F. E. Lewis. W-5500. Vol. XXIII, p. 470, Sept., '26.

**IX—The Testing of Elevator Equipments**—D. Sartini. C-6, D-3, I-5, W-5950. Vol. XXIII, p. 572, Nov., '26.

**X—Automatic Elevators**—F. L. Boissonnault. I-9, W-2500. Vol. XXIV, p. 111, Mar., '27.

**XI—High-Speed Elevator Developments**—E. M. Bouton. C-2, I-3, W-3200. p. 299, June, '27.

**Vertical Transportation—A Summary of the Present ELEVATOR Situation**—H. D. James. T-2, I-1, W-2890. Vol. XXV, p. 285, June, '28.

**Methods of Selecting Electric ELEVATORS**—L. J. Kinnard. T-2, W-1600. Vol. XXV, p. 538, Nov., '28.

**Motor Drive for the World's Largest FERRIES.** I-1, W-200. Vol. XXV, p. 520, Oct., '28.

**Motors and Control for Pulverized FUEL Plants**—M. B. Wyman. I-6, W-6340. Vol. XXIII, p. 236, May, '26.

**Steam Railroad Electrification in the LUMBER Industry**—P. B. Garrett. T-1, C-1, I-6, W-2700. Vol. XXIV, p. 547, Nov., '27.

**Electric Drive and Magnetic Control for MACHINE TOOLS**—A. L. Harvey. I-9, W-2150. Vol. XXI, p. 265, June, '24.

**Direct-Current Machines for Merchant MARINE Drive**—H. E. Stokes. I-10, W-1320. Vol. XXI, p. 520, Nov., '24.

**Electricity in the Modern NEWSPAPER Plant**—H. C. Jorstad. I-10, W-2800. Vol. XXIV, p. 194, May, '27.

(E) Chas. R. Riker. W-830, p. 193.

**Speed Regulating Controllers for Sectional PAPER MACHINE DRIVES**—R. T. Kintzing. C-1, D-1, I-3, W-4450. Vol. XXIII, p. 163, Apr., '26.

**Squirrel-Cage Motors Driving Centrifugal PUMPS**—QB, 2637.

**Electrical Equipment In RAILROAD SHOPS**—W. W. Reddie. (E) W-520. Vol. XXI, p. 258, June, '24.

**Industrial Motor Applications With Especial Reference to the RUBBER Industry**—A. P. Regal. T-1, I-4, W-2950. Vol. XXV, p. 395, Aug., '28.

**The Electric Cargo Winch for SHIPBOARD Service**—A. O. Loomis. I-8, W-3900. Vol. XXI, p. 568, Dec., '24.

**Characteristics of Direct-Current Motors and Generators for Diesel-Electric SHIP PROPULSION**—C. T. Pearce. I-7, W-2450. Vol. XXV, p. 135, Mar., '28.

**SHOVEL Electrification with Alternating-Current Equipment**—R. W. McNeill. I-9, W-2170. Vol. XXII, p. 82, Feb., '25.

**The Electric SHOVEL**—J. E. Borland. C-1, D-1, I-8, W-3250. Vol. XXV, p. 209, May, '28.

**Motors and Control for STOKER Drive**—Ralph Kelly. C-3, I-4, W-2540. Vol. XXI, p. 221, May, '24.

**The Master "Mind" of the Holland TUNNEL**—J. P. Maxwell. D-2, I-8, W-4200. Vol. XXV, p. 17, Jan., '28.

**Motor-Operated VALVES for Use in Steam, Water, Oil, Gas and Air Lines**—C. H. Beckwith. I-2, W-2280. Vol. XXIII, p. 611, Dec., '26.

**VENTILATING the New Liberty Tunnel in Pittsburgh**—Arthur McGonagle. T-1, D-2, I-9, W-3150. Vol. XXII, p. 102, Mar., '25.

**VENTILATION of the Holland Tunnel, New York**—R. E. Bedworth and E. B. Dawson. T-1, C-2, D-2, I-9, W-3600. Vol. XXIV, p. 533, Nov., '27.

(E) Chas. R. Riker. W-700, p. 532.

**A Modern WOOD-VENEER Plant**—F. L. Boissonnault. C-1, D-2, I-6, W-2890. Vol. XXIII, p. 394, Aug., '26.

### *Steel Mills*

**Steel Mill Improvements**—Brent Wiley. (E) W-270. Vol. XXI, p. 402, Sept., '24.

**The Bar Mill and Structural Mill Electrification of the Phoenix Iron Co.**—J. S. Erichson. C-1, I-8, W-2700. Vol. XXI, p. 403, Sept. '24.

**New Motor Drives on Sheared Plate Mills at South Works of Illinois Steel Co.**—W. S. Hall. I-3, W-1300. Vol. XXI, p. 407, Sept., '24.

**Analysis of Oil Circuit Breaker Requirements for Large Steel Plants**—M. J. Wohlgemuth. D-7, W-1850. Vol. XXI, p. 411, Sept., '24.

**The Rehabilitation of Steel Mills**—J. M. Moore and H. M. McLain. C-2, I-5, W-2450. Vol. XXI, p. 424, Sept., '24.

**The Synchronous Motor in Steel-Mill Service**—D. W. Dean. C-5, I-5, W-3900. Vol XXI, p. 428, Sept., '24.

**Power Service for the Steel Industry in the Pittsburgh District**—Chas. R. Riker. W-2340. Vol. XXI, p. 442, Sept., '24.

**Electrification of Blast-Furnace Bell Hoists**—G. W. Baumgarten. D-2, I-1, W-1630 Vol. XXI, p. 527, Nov., '24.

**The Interchange of Power between Steel Mills and Central Stations**—S. S. Wales. (E) W-600. Vol. XXII, p. 411, Sept., '25.

**The Steel Mill as a Motor Proving Ground**—Chas. R. Riker. (E) W-800. Vol. XXII, p. 412, Sept., '25.

**The Trend of Steel Mill Rehabilitation**—Wilfred Sykes. W-1550. Vol. XXII, p. 413, Sept., '25.

**Advantages of Adjustable-Speed Drives for Rolling Mills**—Wm. B. Shirk. I-6, W-1800. Vol. XXII, p. 414, Sept., '25.

**Steel Enclosed Switching Equipment for Steel Mill Service**—M. J. Wohlgemuth. I-9, W-1280. Vol. XXII, p. 417, Sept., '25.

**Wound-Rotor Induction Motors and Synchronous Motors for Rolling Mill Service**—G. E. Stoltz. C-6, D-2, I-2, W-5150. Vol. XXII, p. 421, Sept., '25.

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**Automatic Substations in Steel Mills**—G. P. Wilson I-4, W-3190. Vol. XXII, p. 428, Sept., '25

**What Is a Reasonable Stock of Renewal Parts**—A. G. Ahrens. W-2500. Vol. XXII, p. 432, Sept., '25.

**Auxiliary Applications in Steel Mills**—Phelan McShane. W-700. Vol. XXII, p. 434, Sept., '25.

**Electrical Maintenance in the Steel Mills**—A. J. Standing (E) W-620. Vol. XXIII, p. 272, June, '26.

**Developments in Steel-Mill Maintenance Practice**—A. C. Cummins. (E) W-1020. Vol. XXIII, p. 273, June, '26.

**Increasing the Use of Electricity in Steel Mills**—G. E. Stoltz. (E) W-1080. Vol. XXIII, p. 274, June, '26.

**Reducing Steel-Mill Operating Costs**—Brent Wiley. (E) W-400. Vol. XXIII, p. 275, June, '26.

**Converting Existing Rolling Mills from Steam Engine to Electric-Motor Drive**—D. M. Petty. I-4, W-2260. Vol. XXIII, p. 276, June, '26.

**Electric Furnaces for Castings and Ingots**—Edward T. Moore. C-1, I-8, W-3420. Vol. XXIII, p. 279, June, '26.

**Steel-Mill Motor Ventilation**—R. T. Thornton. C-1, I-5, W-1840. Vol. XXIII, p. 284, June, '26.

**Power-Factor Correction in Steel Mills**—E. F. Rhodes. I-8, W-1090. Vol. XXIII, p. 287, June, '26.

**Demagnetization of Iron and Steel**—Guerney H. Cole. T-2, C-10, I-4, W-4160. Vol. XXIII, p. 289, June, '26.

**Recent Developments in Switching Equipment for Industrial Plant Electrification**—M. J. Wohlgemuth. I-4, W-750. Vol. XXIII, p. 298, June, '26.

**Reversing Mill Driving Equipments**—H. E. Stokes. C-6, I-4, W-3640. Vol. XXIII, p. 306, June, '26.

**Truck-Type Switching Equipment for Industrial Plants and Steel Mills**—M. H. Hobbs. D-1, I-5, W-1470. Vol. XXIII, p. 319, June, '26.

**Steel Mill Ingot Handling Equipment**—P. McShane. I-1, W-1560. Vol. XXIII, p. 559, Nov., '26.

**Operator's Relation to Safety in Steel Mills**—A. J. Standing. (E) W-700. Vol. XXIV, p. 308, July, '27.

**Standardization in the Steel Industry**—Geo. H. Schaeffer. (E) W-500. Vol. XXIV, p. 310, July, '27.

**Electric Drive for Ten-Inch Strip Mill at Laclede Steel Co.**—A. F. Kenyon. T-1, D-1, I-7, W-4000. Vol. XXIV, p. 312 July, '27.

**New Steel Mill Installation of the Pacific Coast Steel Company**—Wallace Eshelman. I-3, W-910. Vol. XXIV, p. 318, July, '27.

**Manipulation of Steel**—Phelan McShane. T-1, C-2, I-1, W-1800. Vol. XXIV, p. 319, July, '27.

**1500 Horse-Power Kraemer Speed Set for the Columbia Steel Corporation, Pittsburgh, Calif.**—E. A. Slater, D-1, W-1000. Vol. XXIV, p. 322, July, '27.

**Electric Heat and the Steel Industry**—W. J. Diederichs. I-7, W-2100. Vol. XXIV, p. 323, July, '27.

**Steel-Mill Type Safety Switches**—W. B. Shirk. C-1, I-5, W-2400. Vol. XXIV, p. 327, July, '27.

**Building a Mill Around a Motor**—G. E. Stoltz. (E) W-700. Vol. XXIV, p. 415, Sept., '27.

**Electrification of Rolling Mills in the Structural Department, Homestead Works, Carnegie Steel Company**—R. H. Wright. D-1, I-11, W-4400. Vol. XXIV, p. 419, Sept., '27.

**Control for Automatic Screw Down on a Rolling Mill**—H. C. Jenks, I-8, W-3300, Vol. XXIV. p. 446. Sept., '27.

**The Value of Electrification to the Steel Mill Industry**—Brent Wiley. W-2050. Vol. XXV, p. 321, July, '28.

**The Electrification of No. 3 Rod Mill at the Worcester Works of the American Steel and Wire Co.**—G. P. Wilson. C-1, I-10, W-1750. Vol. XXV, p. 323, July, '28.

**Structural Features of an 8000 Hp Reversing Direct-Current Mill Motors**—H. E. Stokes and C. P. Croco. I-5, W-1700. Vol. XXV, p. 348, July, '28.

### *Vehicles*

**Motors for Commercial Electric Vehicles**—C. A. Atwell. C-4, I-2, W-1360. Vol. XXI, p. 33, Jan., '24.

**Build Up the Electric Truck Industry**—H. B. Smith. (E) W-1200. Vol. XXI, p. 131, Apr., '24.

**Electric Vehicle Schools**—E. S. Mansfield. (E) W-500. Vol. XXI, p. 132, Apr., '24.

**The Relation of the Central Station to the Electric Truck Industry**—Chas. R. Skinner. W-1320. Vol. XXI, p. 133, Apr., '24.

**Bakery Deliveries with Electric Trucks Delivering the Goods in Chicago**—L. M. Branch. I-1, W-1050. Vol. XXI, p. 134, Apr., '24.

**Electric Truck Battery Charging Equipment**—Otto Sarvas. D-3, I-5, W-2500. Vol. XXI, p. 136, Apr., '24.

**Mechanical Features for Motors and Generators for Gas-Electric Buses**—C. A. Atwell. I-9, W-1700. Vol. XXV, p. 392, Aug., '28.

**A New Gas Electric Truck.** W-400. Vol. XXV, p. 159, Mar., '28.

## Heating Apparatus

**Industrial Electric Heating**—Wirt S. Scott. W-3100. Vol. XXI, p. 229, May, '24.

**Operating Costs and Industrial Electric Heating**—Wirt S. Scott. I-4, W-930. Vol. XXI, p. 283, June, '24.

**Manufacturing by Electric Heat**—W. S. Scott. T-2, I-9, W-5700. Vol. XXIII. p. 548, Nov., '26.
(E) Chas. R. Riker. W-450, p. 547.

**Electrically-Heated Commercial Cooking and Baking Equipment**—Sales and Load Possibilities—R. H. MacGillivray. T-1, W-1820. Vol. XXIII, p. 592, Dec., '26.

**The Bimetallic Disc Type Thermostat**—V. G. Vaughan. C-1, I-4, W-1400. Vol. XXI, p. 532, Nov., '24.

**Status of Small Arc Furnace for Melting Steel**—G. H. Schaeffer. (E) W-400. Vol. XXI, p. 401, Sept., '24.

**Electric Heat**—Geo. H. Schaeffer. (E) W-600. Vol. XXII, p. 410, Sept., '25.

**Electric Furnaces for Castings and Ingots**—E. T. Moore. C-1, I-8, W-3420. Vol. XXIII, p. 279, June, '26.

**Heating a Large Generator Rotor by Induction**—G. C. Heckman. C-3, D-1, I-1, W-1800. Vol. XXIII, P. 467, Sept., '26.

**Industrial Electric Heating Accomplishments**—W. H. Sammis. (E) W-500. Vol. XXIV, p. 246, June, '27.

**Electric Heat and the Steel Industry**—W. J. Diederichs. I-7, W-2100. Vol. XXIV, p. 323, July, '27.

**Electric Snow Melters Protect Switch Tracks.** I-1, W-200. Vol. XXIV, p. 562, Nov., '27.

**Electric Heat In Railway Repair Shops**—ROD, XXI, p. 176.

**Babbitting Pots and Equipment**—ROD XXI, p. 490.

**Mercury Gap for High Frequency Furnace**—QB, 2416.

**Induction-Type Electric Furnaces**—QB, 2563

**Cement to Exclude Air from Heating Element**—QB, 2573.

**Formation of Scale on Immersion Heaters**—QB, 2595.

**Welding Heating Element Wire**—QB, 2696.

### WELDING

**The Selection of a Single-Operator Arc-Welding Motor-Generator Set**—M. S. Hancock. C-2, W-3300. Vol. XXI, p. 269, June, '24.

**Arc Welding and Cutting in Railroad Shops**—A. M. Candy. I-8, W-1310. Vol. XXI, p. 273, June, '24.

**The Development of the Electric Arc Welding Process**—A. R. Allard. I-7, W-3650. Vol. XXV, p. 423, Sept., '28.

**Changing from Cast Iron and Steel to Fabricated Steel**—H. V. Putman and C. C. Brinton. I-16, W-3050. Vol. XXV, p. 333, July, '28.

**Standard Line of Direct-Current Machines Fabricated by Arc Welding**—R. S. Marthens, C. C. Brinton and F. T. Hague. I-8, W-4000. Vol. XXV, p. 575, Dec., '28.

**Testing an Arc Welded Building**—A. M. Candy. T-6, C-5, I-20, W-3980. Vol. XXIV, p. 276, June, '27.

**An Arc-Welded Bridge.** I-1, W-150. Vol. XXV, p. 38, Jan., '28.

**Principle of Operation of a Series Arc Generator**—QB, 2323.

**Welding Heating Element Wire**—QB, 2696.

**Porous Welds**—QB, 2778.

## Magnets

**Pull Obtainable from Lamp Socket**—QB, 2324.

**Brake Coil for Double Voltage**—QB, 2399.

**Noisy Brake Magnets**—QB, 2670.

# INTELLIGENCE TRANSMISSION

## Telegraphy

**The Multiplex Printing Telegraph System**—W. A. Houghtaling. D-1, I-10, W-4540. Vol. XXIII, p. 455, Sept., '26.

## Radio

**Radio Receiving Tube Characteristics**—H. M. Freeman. T-1, C-9, D-2, W-7650. Vol. XXII, p. 584, Dec., '25.

**Improved Radio Broadcasting Service**—H. P. Davis. (E) W-1450. Vol. XXI, p. 2, Jan., '24.

**Radio Station KFKX—The Repeating Broadcasting Station at Hastings, Nebr.**—D. G. Little and F. Falknor. C-3, D-6, I-5, W-3670. Vol. XXI, p. 25, Jan., '24.

**The Elimination of Radio Disturbances Caused by Cottrell Precipitators**—R. E. Boehler. D-2, W-1300. Vol. XXI, p. 422, Sept., '24.

**Influence of Radio on Power Developments**—Chas. R. Riker. (E) W-1300. Vol. XXII, p. 52, Feb., '25.

**Radio Interference from Dust Precipitators**—QB, 2379.

**Popularizing Instruments for Radio Use**—J. W. Legg. I-10, W-4540. Vol. XXIII, p. 9, Jan., '26.

**Audio-Frequency Transformer Characteristics**—Thos. Spooner. T-3, C-9, D-4, W-5820. Vol. XXIII, p. 367, July, '26.

**Radio Interference from Lines Not in Service**—L. A. Terven. D-1, W-450. Vol. XXIV, p. 13, Jan., '27.

**Radio Frequency Standards**—R. C. Hitchcock. C-10, D-2, I-6, W-6100. Vol. XXIV, p. 430, Sept., '27.

**Piezo-Electric Frequency Control**—R. C. Hitchcock. W-600. Vol. XXV, p. 503, Oct., '28.

**Alternating-Current Operated Radio Receivers**—M. C. Batsel. I-3, W-1300. Vol. XXIV, p. 581, Dec., '27.

**Radio on Locomotives.** W-700. XXV, p. 249, May, '28.

**Filter for Radio Rectifier**—QB, 2508.

**Locating Radio Interference Caused by High-Voltage Power Lines**—QB, 2522.

**Noise in Generator for Wireless Service**—QB, 2656.

**Resistance-Coupled Amplifier with C Battery**—QB, 2662.

**B—Eliminator Filter Circuit**—QB, 2697.

**Radio Set Characteristics**—QB, 2706.

**BX Instruments Used on Radio Sets**—QB, 2746.

**Radio Terminology**—QB, 2764.

**Radio Interference from Repulsion Motor**—QB, 2784.

**Electrolytic Condenser for B-Eliminator Filter Circuit**—QB, 2788.

**Testing Radio Transformers**—QB, 2817.

**Elimination of Radio Interference**—QB, 2829.

**A Battery Eliminator**—QB, 2837, 2848.

**Television Broadcast**—QB, 2869.

### SIMILAR TUBES

**The Photo-Electric Cell as a Smoke Detector**—S. H. Reynolds. I-1, W-1100. Vol. XXIII. p. 135, Mar., '26.

**Stroboscopic-Neon Lamp Method for Measuring the Slip of Induction Motors**—Carl C. Nelson. I-4, W-1050. Vol. XXV, p. 163, Mar., '28.

**The Grid Glow Tube Relay**—D. D. Knowles. C-2, I-4, W-2050. Vol. XXV, p. 176, Apr., '28.

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# RAILWAY ENGINEERING

(SEE ALSO CONTROLLERS, P. 11; AND SERIES MOTORS, P. 6)

## GENERAL

**Conditions in the Electric Railway Industry**—Britton I. Budd. (E) W-1400. Vol. XXI, p. 455, Oct., '24.

**Observations on the Traction Situation**—F. R. Coates. (E) W-850, Vol. XXI, p. 456, Oct., '24.

**What the Regional Interurban and City Committees May Accomplish for the Electric Railway Industry**—Harry Reid. (E) W-900. Vol. XXI, p. 458, Oct., '24.

**Maintenance of Interurban Car Equipment**—T. H. Nicholl. (E) W-600. Vol. XXI, p. 459, Oct., '24.

**What Does the Interurban Railway Mean to the Economic Development of the Middle West?**—J. A. McGowan. I-2, W-1700. Vol. XXI, p. 460, Oct., '24.

**The Street Congestion Problem**—R. B. Hill. I-3, W-950. Vol. XXI, p. 472, Oct., '24.

**Steam Railroad Suburban Electrification**—A. J. Manson. (E) W-400. Vol. XXII, p. 201, May, '25

**A Word of Encouragement**—John N. Shannahan. (E) I-1, W-1250. Vol. XXII, p. 461, Oct., '25.

**Advertise and Give Service**—Frank R. Coates. (E) W-300. Vol. XXII, p. 462, Oct., '25.

**Service Versus Rate of Fare**—W. H. Sawyer. (E) W-1450. Vol. XXII, p. 463, Oct., '25.

**Electric Railway Financing**—R. P. Stevens. (E) W-700. Vol. XXII, p. 464, Oct., '25.

**To Thine Own Self Be True**—James P. Barnes. (E) W-450. Vol. XXII, p. 465, Oct., '25.

**The Present and Future of the Electric Railway Industry**—Britton I. Budd. (E) W-950. Vol. XXII, p. 465, Oct., '25.

**The Street Railway Engineer**—Charles H. Clark. (E) W-400. Vol. XXII, p. 466, Oct., '25.

**Better Rapid-Transit Service**—M. B. Lambert. (E) W-600. Vol. XXII, p. 468, Oct., '25.

**Electric Railway Operations in 1925—A Statistical Review of Developments during the First Half of the Year**—Edmund J. Murphy. W-1400. Vol. XXII, p. 480, Oct., '25.

**Pittsburgh Awarded Transportation Prize**—A. H. McIntire. (E) I-1, W-800. Vol. XXII, p. 520, Nov., 25

**The Industry is Doing Its Job**—F. R. Coates. (E) W-650. Vol. XXIII, p. 491, Oct., '26.

**Our Major Traction Problems**—R. P. Stevens. (E) W-500. Vol. XXIII, p. 492, Oct., '26.

**Why Greater Transportation Taxes for the Many than for the Few?**—Paul Shoup. (E) W-500. Vol. XXIII, p. 493, Oct., '26.

**Selling Transportation**—L. S. Storrs. (E) W-350. Vol. XXIII, p. 493, Oct., '26.

**What Does a Company Do After It Has Won the Coffin Prize?**—W. H. Boyce. W-1440. Vol. XXIII, p. 561, Nov., '26.

(E) Chas. R. Riker, W-350, p. 547.

**Transportation and Its Relation to Economic Progress**—M. B. Lambert. W-2400. Vol. XXIII, p. 608, Dec., '26.

**Rapid Transit in Large Cities**—Charles Kerr, Jr. W-3220. Vol. XXIV, p. 108, Mar., '27.

**Steam Railroad Electrification**—Britton I. Budd. (E) W-1300. Vol. XXIV, p. 241, June, '27.

**Sound Business Economics vs. Expediency in Urban Transportation**—W. H. Sawyer. (E) I-1, W-1100. Vol. XXIV, p. 473, Oct., '27.

**An Integral Part of the Community**—R. P. Stevens. (E) W-700. Vol. XXIV, p. 474, Oct., '27.

**What the Public Should Know About Electric Railways**—Paul Shoup. (E) W-600. Vol. XXIV, p. 475, Oct., '27.

**Some Facts about Bus Operation and Street Car Operation**—J. H. Hanna. (E) W-400. Vol. XXIV, p. 475, Oct., '27.

**Motor Bus and Electric Railway Maintenance**—Daniel Durie. (E) W-1100. Vol. XXIV, p. 476, Oct., '27.

**Fostering Individual Initiative**—T. Fitzgerald. (E) W-500. Vol. XXIV, p. 477, Oct., '27.

**Improved Relations between the Public and the Railways**—Lucius S. Storrs. (E) W-700. Vol. XXIV, p. 477, Oct., '27.

**Getting the Business**—J. V. Sullivan. (E) W-600. Vol. XXIV, p. 478, Oct., '27.

**What Adequate and Efficient Transportation Means to the Progress of Cities**—Jos. H. Alexander. (E) W-1900. Vol. XXIV, p. 479, Oct., '27.

**Helping to Solve the Urban Transportation Problem**—E. M. Herr. (E) W-1600. Vol. XXIV, p. 481, Oct., '27.

**The Economic Position of the Street Railway**—Leslie Vickers. W-2300. Vol. XXIV, p. 500, Oct., '27.

**Some Problems of the Modern Executive**—James P. Barnes. (E) W-600. Vol. XXV, p. 470, Oct., '28.

**Are We Too Near the Trees to See the Forest?**—Paul Shoup. (E) W-1000. Vol. XXV, p. 471, Oct., '28.

**We are Not Trying to Get Higher Prices for Shop-Worn Goods**—J. H. Hanna. (E) W-600. Vol. XXV, p. 472, Oct., '28.

**Better Transportation**—Clinton E. Morgan. (E) W-800. Vol. XXV, p. 472, Oct., '28.

**Local Transportation Conditions in the United States**—Lucius S. Storrs. (E) W-550. Vol. XXV, p. 473, Oct., '28.

**The Engineer in the Electric Railway Field**—R. H. Dalgleish. (E) W-700. Vol. XXV, p. 474, Oct., '28.

**Opportunity in the Street Railway Industry**—W. T. Rossell. (E) W-450. Vol. XXV, p. 475, Oct., '28.

**Handling Mass Transportation**—Joseph H. Alexander. (E) W-550. Vol. XXV, p. 475, Oct., '28.

**Analyzing the Future**—G. C. Hecker. (E) W-500. Vol. XXV, p. 476, Oct., '28.

## SYSTEMS

### Direct Current

**The Indianapolis & Cincinnati Traction Co.**—G. M. Woods. T-1, I-5, W-2300. Vol. XXI, p. 464, Oct., '24.

**The Piedmont and Northern Railway System**—H. C. Hickock. C-1, I-8, W-2590. Vol. XXII, p. 485, Oct., '25.

**Electric Suburban Service on the Illinois Central Railroad**—C. S. Purnell. I-3, W-3350. Vol. XXIII, p. 533, Oct., '26.

**Steam Railroad Electrification in the Lumber Industry**—P. B. Garrett. T-1, C-1, I-6, W-2700. Vol. XXIV, p. 547, Nov., '27.

### Single Phase

**The Virginian Railway Electrification**—Homer K. Smith. C-4, D-1, I-6, W-2700. Vol. XXI, p. 275, June, '24.

(E) F. H. Shepard. W-650, p. 258.

**New Norfolk & Western Locomotives**—T. C. Wurts. D-1, I-4, W-1960. Vol. XXI, p. 280, June, '24.

**Sixteen Years of Electric Locomotive Service at St. Clair Tunnel of Grand Trunk Railway**—H. L. Kirker. I-4, W-1200. Vol. XXI, p. 474, Oct., '24.

**Great Northern Railway Cascade Electrification**—P. A. McGee. C-2, I-4, W-1420. Vol. XXII, p. 489, Oct., '25.

## MOTIVE POWER

### Locomotives

**Electric Quencher Locomotives for By-Product Coke Plants**—H. H. Johnston. I-4, W-2500. Vol. XXI, p. 517, Nov., '24.

**The Application of Light Traction and Industrial Locomotives**—H. C. Hickock. C-3, I-4, W-5100. Vol. XXIV, p. 168, Apr., '27.

**Radio on Locomotives.** W-700. Vol. XXV, p. 249, May, '28.

**Locomotive and Substation Circuit Breaker**—QB, 2714.

**Supply for Auxiliaries on Electric Locomotives**—QB, 2730.

**Gas Electric Traction**— QB, 2765.

### Cars

**The Gasoline-Electric Car**—A. H. Candee. I-4, W-1900. Vol. XXI, p. 481, Oct., '24.

**Gas-Electric Cars and Diesel-Electric Locomotives**—W. R. Stinemetz. (E) W-700. Vol. XXII, p. 470, Oct., '25.

**The Reading Company's Gas-Electric Rail Car**—D. Wallace Fisher. I-5, W-1240. Vol. XXII, p. 493, Oct., '25.

**Gasoline-Electric Cars for Branch Lines**—T. H Murphy. C-2, I-3, W-2060. Vol. XXII, p. 496, Oct., '25.

**Economic Retirement of Obsolete Cars**—W. J. Clardy. T-4, C-1, I-7, W-2550. Vol. XXII, p. 471, Oct., '25.

**Characteristics of Generators and Motors for Gas-Electric Traction**—C. A. Atwell. C-4, D-2, I-3, W-2880. Vol. XXIII, p. 363, July, '26.

**What the Gas-Electric Car Means to the Railroad**—W. R. Stinemetz. I-1, W-1900. Vol. XXIV, p, 494, Oct., '27.

**Making Electric Railway Cars More Attractive by Modern Illumination**—R. W. Cost. T-1, C-1, I-9, W-2700. Vol. XXIV, p. 219, May, '27.

**Tendencies in the Design of Modern Cars**—G. M. Woods. T-1, I-6, W-1800. Vol. XXIV, p. 483, Oct., '27.

**The Maintenance of Electric Railway Car Wheels**—ROD, XXI, p. 81.

**New Subway Cars for Philadelphia.** W-60. Vol. XXV, p. 350, July, '28.

**Developments in Street Car Drives**—G. M. Woods. (E) W-1200. Vol. XXV, p. 476, Oct., '28.

**The Development of the W-N Drive**—W. A. Brecht. C-4, I-5, W-3100. Vol. XXV, p. 478, Oct., '28.

**Speed in Street Railway Service**—E. J. McIlraith. T-2, C-2, W-1850. Vol. XXV, p. 482, Oct., '28.

**The New Birney Car.** I-2, W-350. Vol. XXV, p. 546, Nov., '28.

**Car Axles**—ROD, XXII, p. 235.

**Exciter for Gas-Electric Cars**—QB, 2642.

### Auto Buses

**Electric Drive Possibilities for Railless Self-Propelled Vehicles**—Karl A. Simmon. I-6, W-1960. Vol. XXII, p. 481, Oct., '25.

**The Economic Utility of the Self-Propelled Bus in Conjunction with Electric Railway Service in California**—Paul Shoup. W-1900. Vol. XXII, p. 478, Oct., '25.

**Electrical Equipment for Gas-Electric Railless Vehicles**—C. K. Lee. C-2, I-5, W-4380. Vol. XXIII, p. 136, Mar., '26.

**Now, as to the Bus**—W. H. Sawyer. (E) W-1100. Vol. XXIII, p. 491, Oct., '26.

**The Gas-Electric Bus for Steam Railway Service**—O. F. Warhus. (E) W-750. Vol. XXIII, p. 494, Oct., '26.

### Maintenance and Repairs

**Maintaining Locomotives and Multiple-Unit Cars**—J. V. B. Duer. (E) W-800. Vol. XXI, p. 257, June, '24.

**Economics in Railway Maintenance**—John S. Dean. W-1900. Vol. XXI, p. 476, Oct., '24.

**Opportunities for Better Maintenance of Equipment**—G. C. Hecker. (E) W-900. Vol. XXII, p. 469, Oct., '25.

**Accurate Records on the Life of Parts**—Necessary as a Guide to the Reduction of Maintenance Costs—John S. Dean. W-1700. Vol. XXII, p. 500, Oct., '25.

**Armature Coils Used to Maintain Railway Motors**—A. C. Roe. T-2, I-23, W-3650. Vol. XXV, p. 489, Oct.; p. 549, Nov., '28.

### RAILWAY OPERATING DATA

**Wrenches and Hand Tools for Overhauling Railway Motors**—ROD, XXI, p. 43.

**The Maintenance of Electric Railway Car Wheels**—ROD, XXI, p. 81.

**Taking Off Railway Motor Pinions**—ROD, XXI, p. 126.

**Electric Heat in Railway Repair Shops**—ROD, XXI, p. 176.

**The Line Switch as an Adjunct in the Reduction of Maintenance of Main Circuit Controllers**—ROD, XXI, p. 254.

**Machining Split-Frame Motors at Bearing and Housing Seats**—ROD, XXI, p. 300.

**Load Test On Repaired Railway Motors**—ROD, XXI, p. 346.

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**Testing Insulating Varnishes**—ROD, XXI, p. 394.

**Testing Railway Motors Under the Car**—ROD, XXI, p. 445.

**Babbitting Pots and Equipment**—ROD, XXI, p. 490.

**Insulating a Railway Motor Armature**—ROD, XXI, p. 535.

**Impregnating Railway Motor Field Coils**—ROD, XXII, p. 95.

**Brushholder Repair Work**—ROD, XXII, pp. 140, 197.

**Car Axles**—ROD, XXII, p. 235.

**Construction and Repair of Field Coils**—ROD, XXII, p. 309.

**Construction and Advantages of High-Grade Armature Coils**—ROD, XXII, p. 361.

**Simplified Theory of Magnetic Blow-Out**—ROD, XXII p. 456

**Babbitt Metal**—ROD, XXII, p. 515

**Standardizing Railway Car Resistors**—ROD. XXII. p. 565.

**Gears and Pinions**—ROD, XXIII. p. 89.

**Railway Motor Gearing**—ROD, XXIII, p 142.

**Improved Methods of Lubricating Railway Motor Bearings**—ROD, XXIII. p. 196.

**Trolley Wheels**—ROD, XXIII, p. 266.

**Trolley Harps and Poles**—ROD, XXIII, p. 333.

**Trolley Bases**—ROD, XXIII, p. 390.

**Maintenance is No Better than the Class of Tools Used**—ROD, XXIII, p. 435.

**Motor Covers and Axle Shields**—ROD, XXIII, p. 484.

**Reclaiming Used Oil and Waste**—ROD, XXIII, p. 541.

**Field Coil Springs, Washers and Shields**—ROD, XXIII, p. 585.

**Direct-Current Railway Motor Ratings**—ROD, XXIII, p. 627.

**Solder for Railway Electrical Work**—ROD, XXIV, p. 46.

**Side Wear of Carbon Brushes**—ROD, XXIV, p. 91.

**Putting Field Coils in Box-Frame Motors**—ROD, XXIV, p. 140.

**Testing Babbitt-Lined Bearing Shells**—ROD, XXIV, p. 188.

**Cable Lead Terminals and Connectors**—ROD, XXIV, p. 231.

**Pinion Seats on Railway Motor Shafts**—ROD, XXIV, p. 302.

**Armature Cores for Railway Motors**—ROD, XXIV, p. 359.

**Motor Cable Leads**—ROD, XXIV, p. 410.

**Spiders for Railway Motor Armatures**—ROD, XXIV, p. 468.

**Insulation of Railway Motor Brush-Holders**—ROD, XXIV, p. 525.

**Mica and Its Application to Railway Equipment**—ROD, XXIV, p. 575.

**Dual Ventilation for Railway Motors**—ROD, XXIV, p. 630.

**Snow Removal Equipment**—ROD, XXV, p. 48.

**Noise Reduction**—ROD, XXV, p. 113.

**Revamping Old Railway Motors with Modern Renewal Parts**—ROD, XXV, p. 201.

**Gear Center Distances on Railway Motors**—ROD, XXV, p. 315.

**Inspection and Upkeep of Drum Type Controllers**—ROD, XXV, p. 368.

### MINING

**Electricity in the Coal Industry**—E. E. Boon. (E) W-600. Vol. XXV, p. 207, May, '28.

**Recent Developments in Mine Mechanization**—Geo. B. Harrington. (E) W-300. Vol. XXV, p. 207, May, '28.

**Electricity, Permissible Equipment and Mechanization**—L. C. Ilsley. (E) W-550. Vol. XXV, p. 208, May, '28.

**Synchronous Motor Applications in the Mining Industry**—H. Speight. D-1, I-9, W-1900. Vol. XXV, p. 219, May, '28.

**The Use of Ball Bearings on Mine Locomotive Motors**—C. A. Atwell. C-1, I-7, W-2500. Vol. XXI, p. 513, Nov., '24.

**Recent Developments in Permissible-Type Equipment**—W. D. Turnbull. I-6, W-1550. Vol. XXV, p. 231, May, '28.

**Large Main Haulage Mine Locomotives**—G. H. F. Holy. T-3, C-1, D-2, I-5, W-1550. Vol. XXV, p. 234, May, '28.

**Organized Maintenance of Electric Locomotives for Coal Mines**—John S. Dean. T-3, I-4, W-2950. Vol. XXV, p. 243, May, '28.

**Special Requirements of Motors for Mine Locomotives**—C. A. Atwell. I-8, W-2300. Vol. XXIV, p. 539, Nov., '27.

**A Mine Locomotive for Thin Seams.** I-1, W-100. Vol. XXIV, p. 493, Oct., '27.

**Conversion Equipment for Mining Substations**—R. E. Powers. I-8, W-3450. Vol. XXV, p. 227, May, '28.

**Trolley Wire for Mine Service**—H. N. Richards. I-3, W-900. Vol. XXV, p. 237, May, '28.

**Automatic Switching Equipment for Mining Substations**—S. M. Dougherty. I-5, W-2450. Vol. XXV, p. 214, May, '28.

**Largest Underground Haulage Locomotive.** I-2, W-400. Vol. XXV, p. 462, Sept., '28.

**Changing Mine Locomotive Trolley Heights** QB, 2821.

# MISCELLANEOUS

### GENERAL

**Working Drawings**—B. Moore. D-2, W-2400. Vol. XXI, p. 483, Oct., '24.

**The Photo-Electric Cell as a Smoke Detector**—S. H. Reynolds. I-1, W-1100. Vol. XXIII, p. 135, Mar. '26.

**Photography of Arcs**—H. W. Tenney. I-11, W-3030. Vol. XXIII, p. 249, May, '26.

**Surge Generating Equipment**—D. F. Miner. C-2, D-14, I-7, W-5360. Vol. XXIII, p. 596, Dec., '26.

**Construction of Audible Warning Signal**—QB, 2585.

**Corrosion of High-Voltage Copper Conductor at Bushings**—QB, 2625.

**Temperature Sensitive Paint**—QB, 2663.

**Heat Radiation from Motor**—QB, 2760.

**Carbon Remover**—QB, 2814.

**Black versus White Paint**—QB, 2862.

### THE ENGINEER

**The Engineer—The Prototype in the Field of Service to Fellowman**—Edwin D. Dreyfus. W-2600. Vol. XXIV, p. 84, Feb., '27.

**A Personal Inventory**—Chas. R. Riker. (E) W-800. Vol. XXIV, p. 95, Mar., '27.

**Mental Hygiene in Everyday Life**—Coleman R. Griffith. W. 6900. Vol. XXIV, p. 101, Mar., '27.

**The Engineer Salesman**—E. H. Sniffin. (E) W-700. Vol. XXIV, p. 415, Sept., '27.

**Organization and Man Power**—R. L. Wilson. (E) W-800. Vol. XXV, p. 59, Feb., '28.

**The Increasing Importance of Craftsmanship**—W. A. Dick. (E) W-300. Vol. XXV, p. 373, Aug., '28.

**The Public Utility Engineer**—E. C. Stone. (E) W-1350. Vol. XXV, p. 527, Nov., '28.

### Road Engineer and Construction

**Hauling Heavy Apparatus**—A. N. Cartwright. I-4, W-1460. Vol. XXII, p. 222, May, '25.

**Mounting Rotors on Shafts in the Field**—E. L. Doty. W-1800. Vol. XXII, p. 220, May, '25.

(E) Chas. R. Riker. W-400, p. 201.

**A Puzzling High-Voltage Disturbance**—E. L. Doty. W-700. Vol. XXII, p. 124, Mar. '25; p. 243, May, '24.

**Unexpected Difficulties**—E. L. Doty, W-600. Vol. XXII, p. 401, Aug., '25.

**Facing the Music**—E. L. Doty. W-700. Vol. XXII, p. 550, Nov., '25.

**A Long Shaft Almost Condemned**—A. W. Copley. W-500. Vol. XXIV, p. 383, Aug., '27.

### Education

**Educational Work in the Electric Railway Industry**—Edward Dana. W-2450. Vol. XXII, p. 475, Oct. '25.

**Educational Work in Electrical Railway Industry**—Edward Dana—W-2100. Vol. XXIII, p. 519, Oct., '26.

**Let Us Train Public-Utility Employees In Economics**—N. C. Miller. W-1600. Vol. XXI, p. 462, Oct., '24.

**Let Your Light So Shine**—Chas. R. Riker. (E) W-800. Vol. XXII, p. 519, Nov, '25.

### Personal

**Ralph E. Gilman—An Appreciation**—E. H. Sniffin. (E) W-650. Vol. XXI, p. 4, Jan., '24.

**The Work of Oliver Heaviside**—B. A. Behrend. D-1, I-1, W-12 000. Vol. XXV, p. 26, Jan.; p. 71, Feb., '28.

**Rudolf Emil Hellmund—An Appreciation**—A. M. Dudley. I-1, W-1150. Vol. XXIII, p. 591, Dec., '26.

**Francis Hodgkinson—An Appreciation**—J. F. Johnson. I-1, W-1900. Vol. XXII, p. 314, July, '25.

**Benjamin Garver Lamme—A Tribute**—H. P. Davis. (E) W-1700. Vol. XXI, p. 853, Aug., '24.

**Kelvin's Contribution to Electrical Engineering**—R. Macrae. W-4500. Vol. XXIII, p. 19, Jan., '26.

### Works Management

**Waste**—Its Prevention and the Freeing of Frozen Assets—T. H. Owens. W-2600. Vol. XXV, p. 428, Sept., '28.

### Patent Law for Engineers

**Patents**—Wesley G. Carr, W-4700. Vol. XXI, p. 98, Mar., '24.

**Patentable Inventions**—How Classified. Defined and Protected—O. B. Buchanan. W-5880. Vol. XXI, p. 143, Apr., '24.

**Novelty, Utility and Abandonment of Patent Applications**—J. R. Langley. W-5180. 243, May, '24.

**The Preparation and Prosecution of Patent Applications**—J. R. Langley. W-5180, Vol. XXI, p. 290, June, '24.

**Inventors and Patentees**—J. R. Langley. W-4180. Vol. XXI, p. 326, July, '24.

**Research as Related to Patents and Patent Litigation**—H. O. Bierman. W-4900. Vol. XXI, p. 369, Aug., '24.

**Rights of Inventors and Patentees**—How Enforced—W. G. Carr. W-4000. Vol. XXI, p. 434, Sept., '24.

**Relations of Inventions and Patents to Development**—O. S. Schairer. W-3300. Vol. XXI, p. 487, Oct., '24.

**Copyrights, Trademarks, Prints and Labels, and Unfair Competition In Trade**—W. G. Carr. W-2480. Vol. XXI, p. 529, Nov., '24.

### ENGINEERING SOCIETIES

**N. E. L. A.**

**The National Electric Light Association**—W. H. Johnson. (E) I-1, W-500. Vol. XXI, p. 183, May, '24.

**Technical National Section of the N. E. L. A.**—H. P. Liversidge. (E) W-830. Vol. XXI, p. 185, May, '24.

**The Prime Movers Committee During 1923 and 1924**—Nicholas Stahl. (E) W-930. Vol. XXI, p. 189, May, '24.

**Past, Present and Future**—I. E. Moultrop. (E) W-400. Vol. XXI, p. 197, May, '24.

**The National Electric Light Association**—Franklin T. Griffith. (E) I-1, W-3700. Vol. XXII, p. 239, June, '25.

**A Brief Review by the Past President**—Walter H. Johnson. (E) W-600. Vol. XXII, p. 246, June, '25.

**The Work of the Technical National Section**—H. P. Liversidge. (E) W-1700. Vol. XXII, p. 246, June, '25.

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**The National Electric Light Association**—J. E. Davidson. (E) W-1050. Vol. XXIII, p. 201, May, '26.

**The Work of the Technical National Section**—C. F. Hirshfeld. (E) W-1000. Vol. XXIII, p. 206, May, '26.

**Logistics of Association Work**—Major H. S. Bennion. (E) W-700. Vol. XXIV, p. 240, June, '27.

**The Work of the Overhead Systems Committee**—H. C. Sutton. (E) W-1000. Vol. XXIV, p. 246, June, '27.

**The Engineering Administration Committee**—A. C. Marshall. (E) W-800. Vol. XXIV, p. 248, June, '27.

**The Engineering National Section**—E. C. Stone. (E) W-700. Vol. XXV, p. 260, June, '28.

**Power Plant Development as Seen by the Prime Movers Committee**—Edwin B. Ricketts. (E) W-500. Vol. XXV, p. 261, June, '28.

**Work of the Underground Systems Committee**—J. W. Sylvester. (E) W-900. Vol. XXV, p. 263, June, '28.

**A. I. & S. E. E.**

**The Association of Iron & Steel Electrical Engineers**—R. S. Shoemaker. (E) I-1, W-900. Vol. XXI, p. 399, Sept., '24.

**Development in the Activity of the A. I. & S. E. E.**—A. C. Cummins. (E) W-1100. Vol. XXI, p. 400, Sept., '24.

**The Iron & Steel Convention Exhibits**—F. W. Cramer. (E) W-630. Vol. XXI, p. 401, Sept., '24.

**The Service of A. I. & S. E. E. to the Industry**—A. C. Cummins. (E) I-1, W-1550. Vol. XXII, p. 409, Sept., '25.

**The Convention**—R. S. Shoemaker. (E) W-250. Vol. XXII, p. 411, Sept., '25.

**The Association of Iron and Steel Electrical Engineers**—Geo H. Schaeffer. (E) W-750. Vol. XXIII, p. 271, June, '26.

**A. E. R. A.**

**Opportunities for the Electric Railway Engineer**—H. A. Johnson. (E) W-750. Vol. XXI, p. 457, Oct., '24.

**The Value of Association Work**—C. P. Billings. (E) W-1400. Vol. XXII, p. 467, Oct., '25.

**Welcome, A. E. R. A.**—John J. Stanley. (E) W-350. Vol. XXIII, p. 495, Oct., '26.

**More Equipment Men's Associations**—E. A. Palmer. (E) W-450. Vol. XXIII, p. 494, Oct., '26.

**What the A. E. R. A. is Doing for the Industry**—R. P. Stevens. (E) I-1, W-1150. Vol. XXV, p. 469, Oct., '28.

## THE JOURNAL

**Twenty Years of Growth**—Chas. F. Scott. (E) W-600. Vol. XXI, p. 52, Feb., '24.

**Planning for the Future**—A. H. McIntire. (E) W-600. Vol. XXIII, p. 3, Jan., '26.

**The Topical Index**—Chas. R. Riker. (E) W-300. Vol. XXIII, p. 3, Jan., '26.

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# INDEX TO AUTHORS


ABBOTT, W. L.
The Function of a Base Load Station (E) .....XXI: May, 194

AHRENS, A. G.
What is a Reasonabe Stock of Renewal Parts? .....XXII: Sept., 432

ALEXANDER, D. F.
The Ventilation of Large Induction Motors .....XXII: Nov., 584
Polyphase Induction Motors with Double-Squirrel-Cage Windings .....XXIII: Jan., 15
Some Accessories Often Used with Large Induction Motors.....XXIV: Jan., 14
Fractional Pitch Winding for Induction Motors .....XXV: Feb., 77
The Polyphase Induction Generator.. .....XXV: Aug., 376

ALEXANDER, JOS. H.
What Adequate and Efficient Transportation Means to the Progress of Cities (E) .....XXIV: Oct., 479
Handling Mass Transportation (E) .....XXV: Oct., 474

ALLARD, A. R.
The Development of the Electric Arc Welding Process. ...XXV: Sept., 423

ALLEN, R. C.
Recent Developments in the Design of Impulse-Reaction Steam Turbines .....XXV: Nov., 534

ANDERSON, HAROLD
High-Pressure Steam; Its Advantages and Disadvantages ..XXIV: Sept., 426

ANDERSON, S. H.
Automatic Substations on Pacific Electric System . ....XXIII: Oct., 496

ARKWRIGHT, P. S.
Public Utilities as Community Builders (E) .....XXII: June, 245
Maintain Progressiveness in the Future (E) .....XXIII: May, 201
We are Still Pioneers in Electric Service (E) .....XXIV: June, 236
The Job of the Electrical Industry (E) .....XXV: June, 256

ASHBAUGH, J. H.
Speed Regulator for Single Motor Drive .....XXI: Aug., 390
The Extended Broad-Range Voltage Regulator .....XXII: Nov., 559
Compensating for Voltage Drop with Automatic Voltage Regulators .....XXIII: May, 243
Protection from Overvoltage Due to Voltage Regulators ..XXIV: Nov., 551
System Stability with Quick-Response Excitation and Voltage Regulators .....XXV: Oct., 504

ASHINGER, H. H.
Uniform Illumination for Streets .....XXIV: Feb., 77

ATHERTON, A. L.
Lightning Protection of Distribution Systems .....XXII: June, 301
220 Kv Lightning Arresters—A New Approach to an Old Problem .....XXV: Mar., 118

ATKINSON, R. W.
A High-Tension Bridge for Measurement of Dielectric Losses in Cables ..... XXII: Feb., 58

ATWATER, D. W.
Lighting of the Holland Tunnel .....XXIV: July, 347

ATWELL, C. A.
Motors for Commercial Electric Vehicles .....XXI: Jan., 33
The Use of Ball Bearings on Mine Locomotive Motors ....XXI: Nov., 513
Characteristics of Generators and Motors for Gas-Electric Traction .....XXIII: July, 363
Special Requirements of Motors for Mine Locomotives ...XXIV: Nov., 539
Mechanical Features for Motors and Generators for Gas-Electric Buses .....XXV: Aug., 392

BAILEY, ALEX. D.
What's New in Prime Movers (E) .....XXIV: June, 242

BALE, L. D.
Pneumatic Control of Direct-Current Power Equipment ....XXIII: Oct., 530

BARNES, JAMES P.
To Thine Own Self Be True (E).... ..... XXII: Oct., 465
Some Problems of the Modern Executive (E) .....XXV: Oct., 470

BARRE, H. A.
Transmission System of the Southern California Edison Company..... ..... XXII: June, 257

BATSEL, M. C.
Alternating-Current Operated Radio Receivers .....XXIV: Dec., 581

BAUMGARTEN, G. W.
Electrification of Blast-Furnace Bell Hoists .....XXI: Nov., 527

BECK, EDWARD
Lightning Arresters for Supervisory Control Systems .....XXIV: Aug., 388
A New Resistor for Use in Measurements of Impulse Voltages and Currents .....XXV: Mar., 157
Apparatus Used in the Investigation of Lightning Phenomena .....XXV: Dec., 591

BECKER, JOS. F.
Progress in Industrial Lighting (E) .....XXIII: May, 207

BECKWITH, C. H.
Motor-Operated Valves for Use in Steam, Water, Oil, Gas and Air Lines .....XXIII: Dec., 611

BEDWORTH, R. E.
The Ventilation of the Holland Tunnel .....XXIV: Nov., 533

BEHREND, B. A.
The Work of Oliver Heaviside..... .....XXV: Jan., 26; Feb., 71

BELKNAP, J. H.
Controller Study for Colleges (E) .....XXIII: Sept., 442

BENNION, MAJOR H. S.
Logistics of Association Work (E) .....XXIV: June, 240
We Must Keep Up With The Procession (E) .....XXV: June, 260

BERGVALL, R. C.
Use of Synchronous Condensers with Three-Winding Transformers..... .....XXI: May, 205

BETHEL, C.
Waste-Packed Bearing Design and Operation .....XXI: Mar., 115
The Importance of Efficient Lubrication of Railway Motors .XXI: Oct., 467

BIERMAN, H. C.
Research as Related to Patents and Patent Litigation.....XXI: Aug., 369

BILLINGS, C. P.
The Value of Association Work (E) ..... XXII: Oct., 467

BLISS, O. J.
Protective Relays for Central Station Systems .....XXII: Dec., 578

BODDIE, C. A.
Resonant Control for Street Lights .....XXIV: Feb., 72
Some Transmission Line Fundamentals .....XXV: Jan., 32; Feb., 82

BOEHLER, R. E.
The Elimination of Radio Disturbances Caused by Cottrell Precipitators .....XXI: Sept., 422

BOISSONNAULT, F. L.
A Modern Wood-Veneer Plant .....XXIII: Aug., 394
Automatic Elevators ..XXIV: Mar., 111

BOON, E. E.
Electricity in the Coal Industry (E) .....XXV: May, 207

BORLAND, J. E.
The Electric Shovel .....XXV: May, 209

BOUTON, E. M.
Electric Elevator Practice ..XXIII
Classification-Power Requirements. .. .....Feb., 52
Slow and Medium Speed Elevators. .....Mar., 125
High-Speed Passenger Elevators. .. .....Apr., 156
Mechanical Equipment and Safety Devices .....July, 379
Signals and Dispatching Systems. .....Aug., 432
High-Speed Elevator Developments .....XXIV: June, 299

BOYCE, W. H.
What Does a Company Do After It Has Won The Coffin Prize? XXIII: Nov., 561

BRANCH, L. M.
Bakery Deliveries with Electric Trucks Delivering the Goods in Chicago.. ..... XXI: Apr., 184

BRECHT, W. A.
The Development of the W-N Drive ..... XXV: Oct., 478

BREISCH, E. W.
Battery Charging with Rectigon Rectifiers .....XXI: Apr., 155

BREISKY, J. V.
A Phase Balance Current Relay of the Negative Phase Sequence Type.... ..... XXI: Feb., 77
Development in the Impedance-Type Relay .....XXIV: Feb., 80
Direct-Current Time-Delay Relays—Moving Vane Type ...XXIV: Apr., 179

BRINTON, C. C.
Changing from Cast Iron and Steel to Fabricated Steel .....XXV: July, 333
Standard Line of Direct-Current Machines Fabricated by Arc Welding .....XXV: Dec., 575

BUCHANAN, O. B.
Patentable Inventions—How Classified, Defined, and Protected ..... ..... XXI: Apr., 148

BUDD, BRITTON I.
Conditions in the Electric Railway Industry (E).....XXI: Oct., 455
The Present and Future of the Electric Railway Industry (E)..... ..... XXII: Oct., 465
Steam Railroad Electrification (E) .....XXIV: June, 241

CALVERT, J. F.
Types of High-Frequency Alternators .....XXIV: Jan., 36
A Practical Application of Graphical Flux Mapping .....XXIV: Nov., 543
Graphical Flux Mapping:
I—Theory and General Discussion .....XXV: Mar., 147
II, III & IV—Fields of Non-Salient Pole Synchronous Machines ..... XXV: April, 179; May, 246; July, 362
V—Direct-Current Motors and Generators .....XXV: Aug., 399
VI—Direct-Current Railway Motor—Salient Pole Synchronous Machine —Universal Motor—Directional Element of a Reverse Current Relay—Three-Pole Magnetic Relay ..... .....XXV: Oct., 510

CAMPBELL, C. B.
The Field and Limitations of Extraction Turbines .....XXIV: Nov., 553

CANDEE, A. H.
The Gasoline-Electric Car..XXI: Oct., 461

CANDY, A. M.
Arc Welding and Cutting in Railroad Shops .....XXI: June, 273
A New Arc Welding Generator..... ..... XXI:Sept., 418
Testing the Design Features of an Arc Welded Building ....XXIV: June, 276

CARR, WESLEY G.
Patents .....XXI: Mar., 98
Rights of Inventors and Patentees—How Enforced .....XXI: Sept., 434
Copyrights, Trademarks, Prints and Labels, and Unfair Competition in Trade .....XXI: Nov., 529

CARSON, A. G.
Automatic Control of Hydro-Electric Plants on the Peshtigo River .....XXIII: Apr., 168

CARTWRIGHT, A. N.
Hauling Heavy Apparatus XXII: May, 222

CASPER, R. M
Improved Field Coil Insulation for Large Salient-Pole Machines..... ..... XXII: Jan., 24
Improved Damper Windings for High-Speed Synchronous Machines..... ..... XXII: Apr., 196
Sheet-Steel Enclosing End Bells.... ..... XXII: May, 224

CLAPP, PAUL S.
The Growth of the Electrical Industry —An Expression of Individualism (E) .....XXIV: June, 239

CLARDY, W. J.
Economic Retirement of Obsolete Cars ..... XXII: Oct., 471

CLARK, CHARLES H.
The Street Railway Engineer (E)... ..... XXII: Oct., 466

CLARKE, C. W. E.
Seal Beach Power Station—Los Angeles Gas & Electric Corporation, ..... XXII: June, 281


Digitized by Google

COATES, FRANK R.
Observations on the Traction Situation (E) ..... XXI: Oct., 456
Advertise and Give Service (E) ..... XXII: Oct., 462
The Industry is Doing its Job (E) ..... XXIII: Oct., 491

COBB, H. E.
Bimetal: The Temperature Sentinel ..... XXV: June, 288
A Thermal Accelerating Relay ..... XXV: July, 345

COLE, GUERNEY H.
The Magnetic Properties of Silicon Steel in a Large Transformer ..... XXI: Jan., 17
Effect of Punching Strains on the Magnetic Properties of Electrical Sheet Steel ..... XXI: Feb., 55
Demagnetization of Iron and Steel ..... XXIII: June, 289

COLEMAN, H. C.
All-Electric Sea-Going Hopper Dredges ..... XXI: Sept., 488

COOK, C. S.
Facing the Facts Regarding Rural Service (E) ..... XXI: May, 196

COOK, W. G.
Inductive Time Limit Control ..... XXV: July, 327

COPE, H. W.
Application Engineering (E) ..... XXIII: Sept., 442
Electrical Developments in 1926 (E) ..... XXIV: Jan., 1
Nineteen Twenty-Seven and Electrical Progress (E) ..... XXV: Jan., 1

COPLEY, A. W.
The Operation of 220 000 Volt Transmission Lines ..... XXI: May, 202
Experience on the Road—A Long Shaft Almost Condemned ..... XXIV: Aug., 383

CORNELIUS, M.
Truck-Type Switching Equipments ..... XXI: May, 225

COST, R. W.
Making Electric Railway Cars More Attractive by Modern Illumination ..... XXIV: May, 219

COX, G. H.
Relations between Central Station Engineers and Prime Mover Manufacturers (E) ..... XXV: Nov., 528

COX, J. H.
The Klydonograph—A Practical Surge Recorder ..... XXIV: Jan., 5
Lightning and Its Effects on Transmission Lines ..... XXIV: Aug., 364

CRABBS, H. J.
Latches and Operating Sticks for Disconnecting Switches ..... XXI: Oct., 478
Disconnecting Switches and Primary Cut-Outs for Overhead Distribution ..... XXII: June, 305

CRAMER, FRANK W.
The Iron & Steel Convention Exhibits (E) ..... XXI: Sept., 401

CRAWFORD, P. O.
Recent Hydro-Electric Development in Southern Oregon and Northern California ..... XXII: June, 278

CREED, WIGGINTON E.
Why Electricity is Cheap (E) ..... XXII: June, 248
Water Power Developments (E) ..... XXIII: May, 205
Economic Laws Apply to Water Power Development (E) ..... XXIV: June, 243

CROCO, C. P.
Structural Features of an 8000 Hp Reversing Direct-Current Mill Motor ..... XXV: July, 348

CUMMINS, A. C.
Developments in the Activity of the A. I. & S. E. E. (E) ..... XXI: Sept., 400
The Service of A. I. & S. E. E. to the Industry (E) ..... XXII: Sept., 409
Developments in Steel Mill Maintenance Practice (E) ..... XXIII: June, 273

CURTIS, J. F.
Renewal Bearings of Graded Diameters for Railway Motors ..... XXII: Oct., 499

DALGLEISH, R. H.
The Engineer in the Electric Railway Field (E) ..... XXV: Oct., 474

DANA, EDWARD
Educational Work in the Electric Railway Industy ..... XXII: Oct., 475
Educational Work in Electric Railway Industry ..... XXIII: Oct., 519

DANN, W. M.
60 000 Kv-a Transformer Banks Equipped for Change of Ratio Under Load ..... XXIII: Aug., 398

DAVIDSON, J. E.
Better Home Lighting Activity (E) ..... XXI: May, 192
"— and a Little Child Shall Lead them" (E) ..... XXII: June, 248
The National Electric Light Association (E) ..... XXIII: May, 201
Making Opportunities for More Engineering (E) ..... XXIV: June, 238

DAVIS, H. P.
Improved Radio Broadcasting Service (E) ..... XXI: Jan., 2
Benjamin Garver Lamme—A Tribute ..... XXI: Aug., 353

DAWE, R. E.
The Insulation and Winding of Induction Regulators ..... XXIV: Aug., 393

DAWSON, E. B.
The Ventilation of the Holland Tunnel ..... XXIV: Nov., 533

DEAN, D. W.
The Synchronous Motor in Steel-Mill Service ..... XXI: Sept., 428
Magnetic Brakes and Their Application ..... XXIV: July, 329

DEAN, JOHN S.
Wrenches and Hand Tools for Overhauling Railway Motors XXI: Jan., 43
The Maintenance of Electric Railway Car Wheels ..... XXI: Feb., 81
Taking Off Railway Motor Pinions ..... XXI: Mar., 126
Electric Heat in Railway Repair Shops ..... XXI: Apr., 176
Machining Split-Frame Motors at Bearing and Housing Seats ..... XXI: June, 300
Load Test on Repaired Railway Motors ..... XXI: July, 346
Testing Insulating Varnishes ..... XXI: Aug., 394
Testing Railway Motors under the Car ..... XXI: Sept., 445
Economies in Railway Maintenance ..... XXI: Oct., 476
Babbitting Pots and Equipment ..... XXI: Oct., 490
Insulating a Railway Motor Armature ..... XXI: Nov., 535
Impregnating Railway Motor Field Coils ..... XXII, Feb., 95
Brushholder Repair Work ..... XXII: Mar., 140; Apr., 197
Car Axles ..... XXII: May, 235
Construction and Repair of Field Coils ..... XXII: June, 309
Construction and Advantages of High-Grade Armature Coils XXII: July, 361
Accurate Records on the Life of Parts Necessary as a Guide to the Reduction of Maintenance Costs ..... XXII: Oct., 500
Babbitt Metal ..... XXII: Oct., 515
Standardizing Railway Car Resistors ..... XXII: Nov., 565
Gears and Pinions ..... XXIII: Feb., 89
Railway Motor Gearing XXIII: Mar., 142
Improved Methods of Lubricating Railway Motor Bearings ..... XXIII: Apr., 196
Trolley Wheels ..... XXIII: May, 266
Trolley Harps and Poles XXIII: June, 233
Trolley Bases ..... XXIII: July, 390
Motor Covers and Axle Shields ..... XXIII: Sept., 484
Reclaiming Used Oil and Waste ..... XXIII: Oct., 541
Field Coil Springs, Washers and Shields ..... XXIII: Nov., 585
Direct-Current Railway Motor Ratings ..... XXIII: Dec., 628
Solder for Railway Electrical Work ..... XXIV: Jan., 46
Side Wear of Carbon Brushes ..... XXIV: Feb., 91
Putting Field Coils in Box-Frame Motors ..... XXIV: Mar., 140
Testing Babbitt Lined Bearing Shells ..... XXIV: Apr., 188
Cable Lead Terminals and Connectors ..... XXIV: May, 231
Pinion Seats on Railway Motor Shafts ..... XXIV: June, 302
Armature Cores for Railway Motors ..... XXIV: July, 359
Motor Cable Leads ..... XXIV: Aug., 410
Spiders for Railway Motor Armatures ..... XXIV: Sept., 468
Insulation of Railway Motor Brushholders ..... XXIV: Oct., 525
Mica and Its Application to Railway Equipment ..... XXIV: Nov., 575
Dual Ventilation for Railway Motors ..... XXIV: Dec., 630
Snow Removal Equipment XXV: Jan., 48
Noise Reduction ..... XXV: Feb., 113
Revamping Old Railway Motors with Modern Renewal Parts XXV: Apr., 201
Organized Maintenance of Electric Locomotives for Coal Mines ..... XXV: May, 243
Gear Center Distances on Railway Motors ..... XXV: June, 315
Inspection and Upkeep of Drum Type Controllers ..... XXV: July, 368

De CAMP, R.
Short-Circuit Calculating Table of the Variable Resistor Unit, Direct Current Type ..... XXIII: June, 299

DEN HARTOG, J. P.
Calculation of Sags in a Transmission Line with a Broken Conductor ..... XXV: Jan., 24

DICK, W. A.
The Increasing Importance of Craftsmanship (E) ..... XXV: Aug., 373

DIEDERICHS, W. J.
Electric Heat and the Steel Industry ..... XXIV: July, 323

DOOLITTLE, H. L.
Hydroelectric Development and Tendencies (E) ..... XXIV: June, 247

DORFMAN, L.
A Unity Power-Factor Constant-Current Regulator ..... XXII: Feb., 86

DOTY, E. L
A Puzzling High-Voltage Disturbance ..... XXII: Mar., 124
Mounting Rotors on Shafts in the Field ..... XXII: May, 220
Unexpected Difficulties ..... XXII: Aug., 401
Facing the Music ..... XXII: Nov., 550

DOUGHERTY, S. M.
Automatic Switching Equipment for Mining Substations ..... XXV: May, 214

DOVJIKOV, A.
Impedance of a Rotating Synchronous Machine to a Negative Sequence Voltage ..... XXIV: Mar., 117

DREYFUS, EDWIN D.
Managerial Burden in Large Enterprises (E) ..... XXII: June, 253
The Engineer—The Prototype in the Field of Service to Fellowmen ..... XXIV: Feb., 84
Economic and Governmental Regulation Inseparably Mixed (E) ..... XXV: June, 264

DUDLEY, A. M.
Induction Motors on Unbalanced Circuits—Vector Methods of Analysis of Unsymmetrical Systems ..... XXI: July, 339
Lap Windings with Unequal Coil Groups ..... XXII: Jan., 25
Five Years More Life (E) ..... XXIII: Sept., 444
Rudolf Emil Hellmund—An Appreciation ..... XXIII: Dec., 591
How Choose a Motor (E) XXV: Mar., 117
Economic Principles of Design (E) ..... XXV: Sept., 421

DUER, J. V. B.
Maintaining Locomotives and Multiple-Unit Cars (E) ..... XXI: June, 257

DURIE, DANIEL
Motor Bus and Electric Railway Maintenance (E) ..... XXIV: Oct., 476

DWIGHT, HERBERT BRISTOL
Losses in Grounded Sheaths of Single-Conductor Cables ..... XXI: Feb., 62
Abnormal Behavior of Iron-Cored Reactors in Condensive Circuits ..... XXI: July, 324
A Formula for Use in Calculating Repulsion of Coaxial Coils ..... XXII: Aug., 389
Zero Mutual Inductance Positions of Coils with Parallel Axes ..... XXII: Dec., 583
Alternating-Current Conductivity of Iron Pipe ..... XXIII: June, 295
Traveling Cranes for Handling Freight Cars in Railway Terminal Yards ..... XXIII: Sept., 448
Power-Factor Rate Clauses XXV: Jan., 14
Induced Voltages in Conductors ..... XXV: Apr., 173

EAMES, W. F.
Electric Elevator Practice—IV—Controllers for High-Speed Elevators ..... XXIII: May, 253

EATON, G. M.
The Problem of Vibration (E) ..... XXI: Jan., 4

EDSON, WM. W.
Relaying the 110 000 Volt System of the Edison Electric Illuminating Co., of Boston ..... XXV: Nov., 540

EGLIN, W. C. L.
Present Tendencies in the Design of Large Power Plants (E) XXI: May, 198

ELKER, H. R.
The Purpose and Construction of Commutating Poles ..... XXIII: Nov., 555

ELZI, JOSEPH A.
The Number of Commutating Poles Used in Direct-Current Machines ..... XXII: Mar., 129
Direct-Current Generators for Battery Charging ..... XXIII: July, 351


Digitized by Google

ENGER, ARNE R.
The Contact Resistance of Large Conductors .....XXI: July, 816

ERICHSON, J. S.
The Bar Mill and Structural Mill Electrification .....XXI: Sept., 408

ESHELMAN, WALLACE
New Steel Mill Installation of the Pacific Coast Steel Company .....XXIV: July, 318

EVANS, R. D.
Analytical Solution of Networks..... XXI: Apr., 149; May, 207
Distorted Asymmetric Wave Shapes (E) .....XXIV: Sept., 416
Symmetrical Components:
I—Resolution of Vectors Into Symmetrical Co-ordinates .XXV: Mar., 151
II—Resolution of Three Vector Products Into Products of Their Symmetrical Components ..XXV: Apr., 194
III—Calculation of Unbalanced Faults .....XXV: June, 307
IV—Calculation of Faults on Systems with Lumped Constants ..... .....XXV: July, 359

EWELL, M. M.
Protective Equipment for Direct-Current Networks . .....XXIII: May, 227

FALKNOR, F.
Radio Station KFKX—The Repeating Broadcasting Station at Hastings, Nebr. .....XXI: Jan., 25

FARLEY, W. R.
Control and Relay Equipment for Motor-Operated Transformer Tap Changer . .....XXIV: Sept., 438

FECHHEIMER, C. J.
The Influence of Density Upon the Weight and Volume of Air which Passes Through an Electric Machine . .....XXIII: Feb., 63

FIELD, R. M.
The Step Induction Regulator for Transformer Voltage Control..... .....XXV: July, 351
A New Type of Transformer Tap Changer . .....XXV: Nov., 555

FINDLEY, R. L.
Operation of a Synchronous Motor as Part of a Set .....XXIV: May, 198

FISHER, D. WALLACE
The Reading Company's Gas-Electric Rail Car .....XXII: Oct., 498

FITZGERALD, T.
Fostering Individual Initiative (E) .....XXIV: Oct., 477

FLANDERS, WARREN B.
Some Problems in Connection with the Design of Large Turbines .....XXIII: May, 213

FLEMING, T. B.
The Application of High-Tension Insulators .....XXI: May, 217

FLETCHER, L. C.
Balancing Large Rotating Apparatus. ..... XXI: Jan., 5

FLYNN, W. B.
Load Dispatcher's Board of the Georgia Power Company .....XXIV: Dec., 579

FORTESCUE, CHAS, LeG.
A Theory of Lightning ..... .....XXV: May, 223; June, 291

FRANKENBERRY, T. H.
Pole-Type Metering Outfits .....XXIII: Aug., 426

FREEMAN, H M.
Radio Receiving Tube Characteristics .....XXII: Dec., 584

FRENGER, R. F.
Automatic Reclosing Equipment for Alternating-Current Feeders .....XXIII: Apr., 179

FUGILL, A. P.
Motor Performance on Combined Secondary Networks ....XXII: July, 816

GABLE, JOS. A.
Current Carrying Capacity of Bare Cables .....XXIII: Nov., 557

GARRETT, P. B.
Automatic Hydro-Electric Plant of the San Gorgonio Power Company.... ..... XXII: June, 286
Steam Electrification in the Lumber Industry .....XXIV: Nov., 547

GIBBS, J. B.
The Open Delta Connection on a Three-Phase Four-Wire System.... ..... XXI: Jan., 86
Dissimilar Transformers in Delta—Vector Solution ....XXII: Mar., 121
The Taylor Connection for Three-Phase to Two-Phase Transformation .....XXIII: July, 341

GILT, C. M
Kings Highway Substation of the Brooklyn Edison Company ..... ..... XXII: Nov., 521

GODIN, R. N.
Automatic Substations on the Montreal & Southern Counties Railway .....XXIII: Oct., 521

GOLLADAY, L. R
Choke Coil Terminals ..XXIII: Mar., 112

GRAHAM, QUENTIN
Pulsations in Power Due to Synchronous Motor-Driven Compressors..... ..... XXI: Feb., 70
A New High-Torque Synchronous Motor . .....XXIII: Jan., 30

GRAVES, J. M.
The Nation's Power Metropolis (E) .....XXIII: May, 210

GRAYBILL, J. H.
The Control of Synchronous Motors.. ..... XXI: July, 885

GREEN, H. H.
Relay Practice .....XXI: July, 819

GREENWOOD, C. ERNEST
The Engineer Has a Sales Objective.. (E) .....XXV: June, 259

GRIFFITH, COLEMAN R.
Mental Hygiene in Everyday Life .....XXIV: Mar., 101

GRIFFITH, FRANKLIN T.
The National Electric Light Association (E) .....XXII: June, 289

GRISCOM, S. B.
A Mechanical Analogy to the Problem of Transmission Stability .....XXIII: May, 230
Characteristics of Ground Faults on Three-Phase Systems. XXIV: Apr., 151

GRISSINGER, G. G.
Recent Developments in Automatic Network Units .....XXII: July, 336
Recent Development in Automatic Network Protectors ..XXIV: Dec., 583

GUIN, L. W.
A Comparison of Street Light Control Methods . .....XXIV: Sept., 444

GULLIKSEN, F. H.
A New Automatic Synchronizer..... .....XXV: June, 295

HAGAN, J. S.
Automatic Substation Equipment of the Staten Island Rapid Transit Railway Company . ..XXIII: Oct., 499

HAGUE, F. T.
Ventilation and Noise Control of Sub-Station Machinery.....XXI: Mar., 107
Standard Line of Direct-Current Machines Fabricated by Arc Welding .....XXV: Dec., 575

HAIL, J. C.
$8 000 000 for Light—Installation of First Unit of New Street Lighting System for St. Louis.XXIV: Feb., 65

HALL, R. L.
Sound-Proof Automatic Substations .....XXIV: June, 273

HALL, W. S.
New Motor Drives on Sheared Plate Mills at South Works of Illinois Steel Company.....XXI: Sept., 407

HAMILTON, WM. R.
Operating Problems of Interconnected Power Systems . .....XXV: Oct., 494

HANCOCK, M. S.
The Selection of a Single-Operator Arc-Welding Motor-Generator-Set.. ..... XXI: June, 269
Direct-Current Dynamometers ..... ..... XXII: Aug., 885
Selecting the Most Desirable Type of Direct-Current Generator ..... .....XXV: Mar., 141

HANKER, F. C.
Problems Arising from the Expansion and Interconnection of Power Systems . .....XXIV: Mar., 96

HANNA, J. H.
Some Facts about Bus Operation and Street Car Operation (E) .....XXIV: Oct., 475
We Are Not Trying To Get Higher.. Prices for Shop-Worn Goods (E).. .....XXV: Oct., 472

HANZLIK, H. J.
165 000 Kw Turbine Generator for Hell Gate .....XXV: June, 274

HARDING, W. R.
Electric Elevator Practice—V—D. C. Elevator Motors ....XXIII: June, 322

HARRER, W. J.
Testing Large Power Transformers .....XXIV: June, 291

HARRINGTON, GEO. B.
Recent Developments in Mine Mechanization (E) .....XXV: May, 207

HARRINGTON, G. F.
Technique of Dufour Cathode-Ray Oscillograph for the Study of Short-Time Phenomena .....XXIV: Aug., 884

HARRISON, A. M.
Graphical Flux Mapping:
I—Theory and General Discussion... .....XXV: Mar., 147
II, III & IV—Fields of Non-Salient Pole Synchronous Machines .... .....XXV: April, 179; May, 246; July, 362
V—Direct-Current Motors and Generators .....XXV: Aug., 399
VI—Direct-Current Railway Motor-Salient Pole Synchronous Machine—Universal Motor—Directional ... Element of a Reverse-Current Relay—Three-Pole Magnetic Relay... .....XXV: Oct., 510

HARVEY, A. L.
Electric Drive and Magnetic Control for Machine Tools.....XXI: June, 265
Control of Electric Motors on Circuits with Fluctuating Voltage ..... ..... XXII: Mar., 128

HARVEY, DEAN
Insulating Oils for Oil Circuit Breakers ..... XXI: Dec., 578
Electrical Insulating Oil ..... .....XXV: Feb., 96; Mar., 127

HARVEY, JAS. H.
Commutator Flashovers in Generators and Motors .....XXIII: Nov., 583

HATHAWAY, C. B
Selecting Motors for Frequent Starting—Importance of Armature Speed and Moment of Inertia XXII: Feb., 89

HAVERSTICK, E. J.
Low Voltage Cutouts for Series ..... Street-Lighting Transformers ..... .....XXV: July, 340

HAYES, STEPHEN Q.
Interconnection, Super-Power and Electrification .....XXI: Feb., 72; .....Mar., 118; Apr., 166; May, 247

HEBREW, J. S.
"No-Winding" Reactors for Paralleling Transformers and for Secondary Network .....XXIII: June, 329

HECKER, G. C.
Opportunities for Better Maintenance of Equipment (E) ....XXII: Oct., 469
Analyzing the Future (E) ..... .....XXV: Oct., 476

HECKMAN, A.
Testing Large Power Transformers .....XXIV: June, 291

HECKMAN, GEO. C.
Heating a Large Generator Rotor by Induction .....XXIII: Sept., 467

HEINZE, CARL A.
Electrical Distribution in Los Angeles ..... XXII: June, 261

HELANDER, LINN
Power Plant Unit Costs and Their Engineering Significance XXI: June, 285

HENDERSON, S. L.
Hot Spot Temperature Measurement in Alternating-Current Generators .....XXIII: Mar., 95
Transposed Armature Coils in Alternating-Current Generators .....XXIII: July, 348
Load Stability (E) ....XXIII: Aug., 393

HERR, E. M.
The Development of Our Electric Service (E) .....XXIV: June, 241
Helping to Solve the Urban Transportation Problem (E) .....XXIV: Oct., 481

HESTER, E. A.
The Electrical Circuits and Switching Equipment of the Hudson Avenue Station of the Brooklyn Edison Company .....XXII: Apr., 166

HIBBEN, S. G.
Good Light—An Oil for Human Machines .....XXII: Dec., 569

HICKOCK, H. C.
The Piedmont and Northern Railway System .....XXII: Oct., 485
The Application of Light Traction and Industrial Locomotives .....XXIV: Apr., 168

HILDENBRAND, H. L.
The Phase Rotation Indicator .....XXIII: Feb., 57
Synchronous Converter Copper Loss .....XXIII: Mar., 110

HILL, C. F.
Effects of Corona in Various Gases on Insulation and Losses..... .....XXV: Aug., 402


Digitized by Google

HILL, L. H.
A Valve for Transformer Radiators ....XXII: Jan., 45
Transformer Voltage Ratio Control under Load .....XXIII: May, 261
The Modern Manufacture of Large Power Transformers XXIV: Apr., 146 ..... May, 203
Forced Air-Blast Equipment for Oil-Immersed Transformers .....XXV: Feb., 60
Recent Developments in Current-Limiting Reactors .....XXV: Mar., 131
Phase-Angle Control Under Load by Means of Transformer Tap Changing Equipment .....XXV: Apr., 183

HILL, ROBERT B.
The Street Congestion Problem..... XXI: Oct., 472

HIPPLE, J. M.
So Trim Your Sails (E) .....XXIII: Sept., 441

HIRSHFIELD, C. F.
The Work of the Technical National Section (E) .....XXIII: May, 206

HITCHCOCK, R. C.
Radio Frequency Standards .....XXIV: Sept., 430
Piezo-Electric Frequency Control .....XXV: Oct., 503

HOBBS, M. H.
Truck Type Switching Equipment for Industrial Plants and Steel Mills .....XXIII: June, 319
Serving the Isolated Load .....XXIV: June, 258

HODGKINS, CHARLES H.
The Adaptation of Formed Steel to Motor Control Apparatus..... XXI: Jan., 30

HODGKINSON, FRANCIS
Steam Turbines and Condensing Equipment ..XXI: Nov., 505; Dec., 545

HOLY, G. H. F.
Large Main Haulage Mine Locomotives .....XXV: May, 234

HOUGHTALING, W. A.
The Multiplex Printing Telegraph System .....XXIII: Sept., 455

HUDSPETH, C. C.
Regulators on Network Feeders .... XXII: July, 346

HUMPHREY, GEO. S.
The Charleroi Substation of the West Penn Power Company ..XXI: Nov., 498
The Interconnection of Power Systems Surrounding the Pittsburgh District .....XXIV: June, 251

HUNT, A. D.
Oil Governors for Turbines (E)..... .....XXV: Apr., 167
The Development of Public Utility Prime Movers (E) ....XXV: June, 266

ILSLEY, L. C.
Electricity, Permissible Equipment... and Mechanization (E) XXV: May, 208

IMLAY, L. E.
Mechanical Characteristics of Transmission Lines:
I—Conductor Characteristics—Wind and Ice Loading .....XXII: Jan., 3
II—Span Formulae and General Methods of Calculation XXII: Feb., 53
III—Span Calculations (Concluded) —Conductor Clearances and Accessories .....XXII: Mar., 125
IV & V—Insulators . XXII: Apr., 187; .....May, 225
VI & VII—Transmission Towers—Fundamental Considerations..... .....XXII: July, 356; Aug., 402
VIII—Transmission Towers—Transpositions, Construction Materials and Foundations .....XXII: Sept., 452
IX—Economics of Transmission Line Design .....XXII: Oct., 502
X—Stringing Conductors on Suspension Insulators—Transmission Line Costs .....XXII: Nov., 562
XI—Construction of Long Spans .... ..... XXII: Dec., 596

INMAN, D. E.
Magnetic Control for Synchronous.... Motors .....XXV: Sept., 431

INSULL, MARTIN J.
Electric Light and Power Investment Companies (E) .....XXII: June, 249

JAMES, H. D.
The Control of Synchronous Motors.. ..... XXI: July, 335
How to Make Controller Diagrams.... ..... XXI: Nov., 523
Vertical Transportation (E) .....XXIII: Feb., 51
Motor Control Development (E)..... .....XXIV: Sept., 417
Changes in Design Practice (E)..... .....XXV: Apr., 167
Vertical Transportation—A Summary of the Present Elevator Situation.. .....XXV: June, 285

JENKS, H. C.
Control for Automatic Screw-Down on a Rolling Mill ...XXIV: Sept., 446

JOHNS, F. J.
High-Slip Versus High-Torque Motors —Their Application and Characteristics .....XXV: Feb., 100

JOHNSON, F. BICE
Influence of Flux on Circuit-Breaker Design .....XXV: June, 312

JOHNSON, HARLEY A.
The Convention Presents Opportunities for the Electric Railway Engineer (E) .....XXI: Oct., 457

JOHNSON, J. F.
Francis Hodgkinson—An Appreciation .....XXII: July, 314

JOHNSON, V. E.
Protective Grounds ..... .....XXV; Aug., 381; Sept., 447

JOHNSON, WALTER H.
The National Electric Light Association (E) .....XXI: May, 188
A Brief Review by the Past President (E) .....XXII: June, 246

JOHNSTON, H. H.
Electric Quencher Locomotives for By-Product Plants.....XXI: Nov., 517
Electrically-Operated Movable Railroad and Highway Bridges .....XXIII: July, 385

JOLLYMAN, J P.
Hydro-Electric System of Pacific Gas & Electric Company ...XXII: June, 274
The Speed Control of a Transmission System ..... ....XXIV: June, 250

JONES, B. M.
The Relaying Problems of a Typical Large Interconnection ..XXV: Apr.,171

JONES, PHILIP CHAPIN
The Economic Balance in Electrical Transmission .....XXII: Jan., 9
The Correction of Power-Factor by the Use of Synchronous Motors .....XXIII: Mar., 99

JONES, W. ALTON
Politics, Propaganda and Public..... Service (E) .....XXV: June, 258

JORSTAD, H. C.
Electricity in the Modern Newspaper Plant .....XXIV: May, 194

JUNKERSFELD, PETER
The New Cahokia Power Station of the Union Electric Light & Power Company, of Illinois ..XXI: May, 232

KELLOGG, DAVID R.
Progress in the Ceramic Industry (E) .....XXIII: July, 337

KELLY, RALPH
Motors and Control for Stoker Drive ..... XXI: May, 221
The Floating Type of House Turbine .....XXII: June, 299
Relay Protection of Power-House Motors .....XXII: Sept., 438

KENYON, A. F.
Effect of Unbalanced Secondary Conditions on the Operation of Large Induction Motors ....XXII: Sept., 435
Electric Drive for Ten Inch Strip Mill at the Laclede Steel Company.... .....XXIV: July, 312

KERR, CHAS., JR.
Rapid Transit in Large Cities..... .....XXIV: Mar., 108

KESTER, C. D.
The Industrial Synchronous Motor (E) .....XXIV: Nov., 531

KINCAID, C. W.
Change-Speed Induction Motors..... ..... XXI: Aug., 357
Polyphase Induction Motors with Double Squirrel-Cage Windings .....XXIII: Jan., 15
Variable-Ratio Frequency Changer Sets .....XXV: June, 279
One Cause of Motor Current Unbalance .....XXV: Sept., 463

KINNARD, L. J.
Methods of Selecting Electric Elevators .....XXV: Nov., 538

KINTZING, R. T.
Speed Regulating Controllers for Sectional Paper Machine Drives .....XXIII: Apr., 163
Control for Direct-Current Industrial Motors .....XXIV: Jan., 23

KIRKER, H. L.
Sixteen Years of Electric Locomotive Service at the St. Clair Tunnel of Grand Trunk Railway...XXI: Oct., 474

KNIGHT, ROGER L.
A Persistent Fallacy (E) XXV: Feb., 58

KNISKERN, F. B.
Oil Switches for Distribution Systems .....XXII: July, 348
How to Select Oil Circuit Breakers .....XXV: Nov., 569

KNOWLES, D. D.
The Grid-Glow Tube RelayXXV: Apr., 176

KRANER, H. M.
Selection of Porcelain for Electrical Purposes .....XXIII: July, 344

KRAUT, S. B.
Testing and Operation of Rectigon Rectifiers .....XXI: Aug., 368

LAFFOON, C. M.
High-Frequency Alternators..... ..... XXI: Sept., 416

LAMBERT, M. B.
Better Rapid-Transit Service (E).... .....XXII: Oct., 468
Transportation and Its Relation to Economic Progress ...XXIII: Dec., 608

LAMME, B. G.
Induction Motor Characteristics and Curves:
I—The Simple Induction Motor..... .....XXIII: Sept., 451
II—Speed-Torque; Current; Power-Factor; Effect of Change in Constants; Maximum Torque; Starting Torque; Frequency ..XXIII: Dec., 614
III—The Circle Diagram—Derivation of Relationships .....XXIV: Jan., 41
IV—Construction of the Circle Diagram .....XXIV: Mar., 132
V and VI—Magnetic Flux Distributions, Magnetomotive Forces and their Influence on Dynamo Construction .....XXIV: May, 213

LANDIS, J. N.
The Construction and Mechanical Features of the Hudson Avenue Station of the Brooklyn Edison Company .....XXII: Apr., 155

LANE, R. A.
Static Condensers for the Higher Distribution Voltages ....XXII: Feb., 68
Measurement of Power-Factor in Industrial Plants .....XXII: Aug., 391

LANGLEY, J. R.
The Preparation and Prosecution of Patent Applications....XXI: June, 290
Inventors and Patentees ..XXI: July, 326

LEACH, FRANK A., JR.
Electric Service on the Pacific Coast (E) .....XXII: June, 252

LEE, COLIN K.
Electrical Equipment for Gas-Electric Railless Vehicles ....XXIII: Mar., 136

LEE, REUBEN
Synchronous Converter Copper Loss .....XXIII: Mar., 110
Some Autotransformer Relations .....XXIII: Nov., 563
Motor Field Rheostat Design ..... .....XXV: Dec., 616
College Laboratory Controllers:
The Unit Panels .....XXIV: Apr., 162
I—D-C. Controllers with Counter E. m. f Acceleration ..XXIV: May, 207
II—D-C. Controllers: Current Limit Acceleration .....XXIV: June, 284
III—D-C. Controllers for Dynamic Braking and Reversing Service.... .....XXIV: July, 352
IV—A-C. Controllers for Squirrel-Cage Motors .....XXIV: Aug., 390
V—A-C. Controllers for Wound-Rotor Motors .....XXIV: Sept., 459
VI—Controllers for Synchronous Motors .....XXIV: Oct., 513
VII—General Considerations .....XXIV: Nov., 566

LEGG, J. W.
The Osiso—A Single-Element Oscillograph of Camera Size..XXI: Dec., 564
A Six-Element Portable Oscillograph—Made Possible by a New Form of Permanent Magnet ....XXII: Mar., 108
Popularizing Instruments for Radio Use .....XXIII: Jan., 9
Oscillography:
I—Types of Oscillographs, Illuminants and Optical Systems..XXIV: June, 268
II—The Osiso in Its Various Forms. .....XXIV: July, 341
III—The Osiso as a Phonoscope for the Deaf .....XXIV: Aug., 398
IV—The Osiso ExhibitorXXIV: Sept., 455
V—The Two-Element Power Osiso.. .....XXIV: Oct., 507
VI—The Multi-Element Oscillograph. .....XXIV: Nov., 557
VII—The Multi-Element Oscillograph and Power Osiso Arranged for Transmission Line Studies..... .....XXIV: Dec., 614
VIII—Auxiliary Apparatus for Staged Tests with the Multi-element Oscillograph .....XXV: Jan., 39
IX—Polyphase Galvanometer Control for the Multi-element Oscillograph .....XXV: Feb., 102
X—Sphere of Applications Expanded with New Galvanometer..... .....XXV: Nov., 557


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LE GHAIT, E. R.
Dielectric Absorption in Fibrous Insulating Materials .....XXII: Nov., 526, Dec., 605
Dielectric Losses in Oil Impregnated Paper .....XXV: Apr., 187

LEHR, E E.
Regulators for Network Distribution Systems .....XXII: July, 344

LEVY, C. C.
Automatic Control for Synchronous Condensers .....XXIII: Apr., 150

LEWIS, F. E.
Electric Elevator Practice—VIII—Installation Tests and Maintenance of Electrical Apparatus .XXIII: Sept., 470

LILJA, E. D.
Automatic Control of Hydro-Electric Plants on the Peshtigo River .....XXIII: Apr., 168

LIPPMAN, H. E.
Lumens Effective on a Street Surface with Directional Control of Light .....XXIV: Feb., 58

LISBERGER, S. J.
The Electric Distribution Network—Of the Pacific Gas & Electric Company .....XXII: June, 268

LITTLE, D. G.
Radio Station KFKX—The Repeating Broadcasting Station at Hastings, Nebr. .....XXI: Jan., 25

LIVERSIDGE, H. P.
Technical National Section of the N. E. L. A. (E) .....XXI: May, 185
The Work of the Technical National Section (E) .....XXII: June, 246

LONGWELL, R. R.
The Avenue T Automatic Supervisory Controlled Substation of the New York Rapid Transit Corporation, Brooklyn, New York, XXIII: Oct., 503

LOOMIS, A. O.
The Electric Cargo Winch for Shipboard Service .....XXI: Dec., 568

LUDWIG, L. R.
The Reason for Chorded Windings.....XXV: Jan., 47
The Lure of the Difficult (E).....XXV: Sept., 421
Surge Voltages Produced by Direct-Current Air Circuit Interrupters.....XXV: Dec., 604

LUKE, GEORGE E.
The Resistance of Electrical Connections .....XXI: Feb., 66

LYNCH, T. D.
The Application of Materials in Design (E) .....XXIII: Mar., 93

LYNN, C.
Stability of Direct-Current Generators at Low Voltages and when Used with Voltage Regulators.....XXI: July, 304

MACGAHAN, PAUL .....
Simplified Practice (E) ..XXI: July, 303
Standardization of Electrical Measuring Instruments (E).....XXV: Dec., 573
Ammeter Shunt for Heavy Capacity Circuits .....XXV: Dec., 615

MACGILLIVRAY, R. H.
Electrically Heated Commercial Cooking and Baking Equipment—Sales and Load Possibilities XXIII: Dec., 592

MACRAE, R.
Kelvin's Contributions to Electrical Engineering .....XXIII: Jan., 19

MANSFIELD, E. S.
Electric Vehicle Schools (E).....XXI: Apr., 132

MALCOLMSON, ROBERT J.
Street Lighting—An Opportunity for Aggressive Sales Effort .XXIV: Feb., 61

MANSON, A. J.
Steam Railroad Suburban Electrification (E) .....XXII: May, 201

MARBURY, R. E.
The Application of Static Condensers to High-Frequency Furnaces .....XXI: Sept., 421
Localized Correction of Power-Factor .....XXI: Dec., 583
Filter Condensers .....XXII: July, 351
Dielectric Absorption in Fibrous Insulating Materials .....XXII: Nov., 526; Dec., 605
Recent Improvements in Static Condensers for Individual Motors .....XXIII: May, 221

MARSHALL, A. C.
The Engineering Administration Committee (E) .....XXIV: June, 248

MARTHENS, R. S.
Standard Line of Direct-Current Machines Fabricated by Arc Welding .....XXV: Dec., 575

MARTIN, E. R.
Maximum Efficiency of Motors .....XXIII: Apr., 161

MARTIN, J. C.
Increasing Co-operation in Inductive Co-ordination Work (E).....XXIV: June, 244

MAXWELL, J. P.
The Master "Mind" of the Holland.. Tunnel .....XXV: Jan., 17

McAULEY, P. H.
Switching-Surge Investigations with the Klydonograph ...XXIV: Jan., 9

McCARTER, THOS. N.
Electric Service in New Jersey (E) .....XXIII: May, 209

McCARTY, R. A.
Hydro-Electric Generator Equipment for Muscle Shoals .....XXI: Apr., 140
A 49 000 Kv-a Frequency Converter Set .....XXIII: July, 339

McCLAIN, J. R.
The Manufacture of Built-Up Mica.. ..... XXI: Jan., 10

McCLOSKEY, F. W.
Sidewear of Brushes in Railway Motors ..... XXII: Oct., 491

McCOY, J. L.
Supervisory Control . ..XXIII: June, 311
All Steel Mounting of Supervisory Control Equipment ..XXIV: June, 296

McGEE, P A.
Great Northern Railway Cascade Electrification .....XXII: Oct., 489

McGONAGLE, ARTHUR
Ventilating the New Liberty Tunnel in Pittsburgh .....XXII: Mar., 102

McGOWAN, JOS. A.
What Does the Interurban Railway Mean to the Economic Development of the Middle West!....XXI: Oct., 460

McILRAITH, E. J.
Speed in Street Railway Service.....XXV: Oct., 482

McINTIRE, A. H.
A World Power Survey (E)..... XXI: Mar., 88
Maintain a Broad Field of Vision (E) ..... XXI: June, 259
Interconnection of Power Systems (E) ..... XXI: Dec., 589
Methods of Testing Electrical Apparatus (E) .....XXII: Jan., 2
Pittsburgh Awarded Transportation Prize (E) .....XXII: Nov., 520
Planning for the Future (E) .....XXIII: Jan., 3
Vital Electric Statistics (E) .....XXIII: May, 212
Conservation in Relation to Mental Limitations (E) .....XXIV: Dec., 578

McLAIN, H. M.
The Rehabilitation of Steel Mills.....XXI: Sept., 424

McLAUGHLIN, H. A.
Development in the Impedance-Type Relay .....XXIV: Feb., 80

McNEILL, R. W.
Shovel Electrification with Alternating-Current Equipment.XXII: Feb., 82
Electrical Equipment for a 30-Inch Diesel-Electric Pipe-Line Dredge .....XXIII: Aug., 403

McNULTY, J. W.
Air Ejectors for Industrial Applications .....XXIV: Oct., 505

McSHANE, PHELAN
Auxiliary Application in Steel Mills.. ..... XXII: Sept., 484
Steel Mill Ingot Handling Equipment .....XXIII: Nov., 559
Manipulation of Steel...XXIV: July, 319

MEYER, H. R.
The Line Switch as an Adjunct in the Reduction of Maintenance of Main Circuit Controllers .....XXI: May, 254
Simplified Theory of Magnetic Blow-Out ..... XXII: Sept., 456
Maintenance is No Better than the Class of Tools Used .XXIII: Aug., 435

MILLER, JOHN B.
Why We Have Split Our Stock (E) .....XXIII: May, 205
Why is Our Industry Suffering from an Inferiority Complex (E) .....XXIV: June, 237
The Intangible Interconnection between Utilities (E).....XXV: June, 256

MILLER, N. C.
Let Us Train Public-Utility Employees in Economics.....XXI: Oct., 462

MINER, D. F.
A Suspension Insulator for High-Voltage Systems .....XXI: Dec., 560
Crest Voltmeters and Their Characteristics .....XXII: Dec., 571
Surge Generating Equipment .....XXIII: Dec., 596
A Million Volt Rectified Surge Generator .....XXIV: June, 287

MONSETH, I. T.
Short-Circuit Calculating Table of the Variable Resistor Unit, Direct Current Type .....XXIII: June, 299

MOON, F. L.
The Effect of the Number of Poles on the Power-Factor of Induction Motors .....XXIII: Aug., 428

MOORE, ARTHUR D.
Mapping Magnetic and Electrostatic Fields .....XXIII: July, 355
The Theory of the Effect of Equalizers in Lap Windings XXIII: Dec., 625

MOORE, B.
Working Drawings ... .XXI: Oct., 488

MOORE, EDWARD T.
Electric Furnaces for Castings and Ingots .....XXIII June, 279

MOORE, J. M.
The Rehabilitation of Steel Mills.... .....XXI: Sept., 424

MORGAN, CLINTON E.
Better Transportation (E) .....XXV: Oct., 472

MOULTROP, I. E.
Past, Present and Future (E)..... .....XXI: May, 197

MURPHY, EDMUND J.
Electric Railway Operations in 1925—A Statistical Review of Developments During the First Half of the Year .....XXII: Oct., 480

MURPHY, T. H.
Gasoline-Electric Cars for Branch Lines .....XXII: Oct., 496

NELSON, C. C.
Stroboscopic-Neon Lamp Method for Measuring the Slip of Induction Motors .....XXV: Mar., 163
Enclosed, Fan-Cooled Motors .....XXV: Aug., 385

NEWBURY, F. D.
Recent Developments in Hydro-Electric Generators .....XXII: May, 210
A New Edition of A. I. E. E. Standards .....XXII: Sept., 447
Metal-Tank Mercury-Arc Rectifiers... .....XXII: Dec., 570
A Survey of Heavy Electrical Machinery Developments XXIII: Apr., 190
Load Division between Alternators... .....XXIV: May, 211
Trends in Turbine Generator Development .....XXIV: July, 334
The Business of Designing Electrical Machinery .....XXV: June, 267

NEWMEYER, W. L.
Automatic Railway Substations in Japan .....XXIII: Oct., 513
Japan from an Electrical Engineer's Viewpoint .....XXV: Jan., 6

NEWTON, R. H.
The Development of Enclosure for Synchronous Converters .....XXV: Dec., 586

NICHOLL, THOS. H.
Maintenance of Interurban Car Equipment (E) .....XXI: Oct., 459

NOTTAGE, S. G.
Dual-Frequency Calender Drive .....XXV: Oct., 500

NYCUM, H. C.
System Stability with Quick-Response Excitation and Voltage Regulators .....XXV: Oct., 504

O'BRIEN, JOHN J.
Management - Investment Companies Mean Greater and Cheaper Service to the Public (E) ....XXII: June, 254
The Importance of Holding Companies to Small Cities, Towns and Farms (E) .....XXIV: June, 244
Electric Industry Faces the Task of Commercial Development (E)..... .....XXV: June, 263

OMAN, CARL
Methods of Metering Energy in Three-Phase, Four-Wire Systems .....XXIII: Sept., 445

OPLINGER, K. A.
Equipment for Controlling the Voltage Ratio of Transformers under Load .....XXIV: Apr., 164

OPSAHL, A. M.
Technique of Dufour Cathode-Ray Oscillograph for the Study of Short-Time Phenomena . ..XXIV: Aug., 384

OWENS, R. W.
Characteristics of Direct-Current Motors .....XXIII: Jan., 37

OWENS, T. H.
Waste—Its Prevention and the Freeing of Frozen Assets..XXV: Sept., 428

OYAMA, MATSUJIRO
The Thermoradiometer and Some Examples of Its Application ..... .....XXIV: Jan., 26


Digitized by Google

PACK, R. F.
"Superpower" and the Farmer (E) ..... XXI: May, 192
Eternal Vigilance (E) ..XXII: June, 244
Cost of Electric Service a Small Percentage of Total Expense (E) .....XXIII: May, 202
Let's Make It Our Business to Sell Electric Energy (E) XXIV: June, 235

PALMER, E. A.
More Equipment Men's Associations (E) .....XXIII: Oct., 494

PARKER, JOHN C.
The "Why" in Hudson Avenue (E) ..... XXII Apr., 150

PARSON, JOHN S.
The Automatic Network Relay ..... XXII: July, 887
Recent Developments in Automatic Network Relays .....XXIV: Dec., 587

PAULSEN, F.
Accelerometers .....XXIII: Sept., 475
Ventilation of Railway Motors .....XXV: May, 251
The Proportionality Chart .....XXV: Aug., 416

PEARCE, C. T.
Effect of Open Circuit in Balance Coil of Three-Wire Generator Using Two Balance Coils .....XXI: Oct., 486
Bearing Currents—Their Origin and Prevention .....XXIV: Aug., 372
Characteristics of Direct-Current Motors and Generators for Diesel-Electric Ship Propulsion .....XXV: Mar., 135
The Operation of Direct-Current Motors in Parallel and Series with Different Types of Load.....XXV: Dec., 581

PEARSON, E. F.
Full Automatic Phase Modifier Station-Northwestern Electric Co. Portland, Ore. .....XXIII: Apr., 154

PERRY, TOM
Full Automatic Phase Modifer Station—Northwestern Electric Co., Portland, Ore. .....XXIII: Apr., 154

PETERS, J. F.
Three-Winding Tansformers .....XXII: Jan., 12; Feb., 71

PETERSON, A. J. A.
Automatic Reclosing Equipment for Alternating-Current Feeders .....XXIII: Apr., 179

PETTY, D. M.
Converting Existing Rolling Mills from Steam-Engine to Electric-Motor Drive .....XXIII: June, 276

PIERCE, R. T.
The Totalization of Power Readings.. ..... XXI: Mar., 103

PIPPITT, P. F.
Types of Commutator Construction .....XXIII: Nov., 565

POWEL, C. A.
Quick-Response Excitation for Alternating-Current Synchronous Machinery .....XXIV: Apr., 157

POWERS, R. E.
Conversion Equipment for Mining Substations .....XXV: May, 227

PRICE, L. D.
Potential Transformer Connections for Three-Phase, Four Wire Metering .....XXIV: Aug., 377

PROCTER, J. H.
Novelty, Utility and Abandonment of Patents .....XXI: May, 243

PROUDFOOT, C. S.
Power Development (E) XXIV: July, 309
Progress and Success of Electrical Engineering (E) .....XXV: July, 320

PURNELL, C. S.
Electric Suburban Service on the Illinois Central Railroad XXIII: Oct., 533

PUTMAN, H. V
Changing from Cast Iron and Steel to Fabricated Steel .....XXV: July, 333

RATHBONE, THOMAS C.
Unusual Vibration of a 250 000 Kw Turbine .....XXV: Feb., 88

REAGAN, M. E.
Methods of Automatically Synchronizing Water-Wheel Generators in Automatic Hydro-Electric Generating Stations .....XXIII: Apr., 172
Automatic Switching Control for Mercury Arc Rectifiers XXIV: Oct., 496

REAST, F. M.
Advantages of Highway Lighting.... ..... XXII: Nov., 548

REDDIE, WM. W.
Electrical Equipment in Railroad Shops (E) .....XXI: June, 258

REED, C. B.
Starting Three-Phase Motors with Autotransformer and with Reactors .....XXIV: May, 224

REED, E. G
Distribution Transformers ..... .....XXII: June, 295
Loading Transformers on a Temperature Basis .....XXII: Nov., 551
The Phase Angle of the Current Transformer .....XXII: Dec., 594
Electrostatic Stresses in Transformers under Operating Conditions .....XXIII: Jan., 32
Current Transformer Calculations .....XXIII: Feb., 67
Approximate Methods of Transformer Design .....XXIII: Nov., 567
Transformer Fundamentals ..... .....XXIV: Jan., 30

REGAL, A. P.
Industrial Motor Applications with Especial Reference to the Rubber Industry .....XXV: Aug., 395

REID, HARRY
What the Regional Interurban and City Committees May Accomplish for the Electric Railway Industry (E) .....XXI: Oct., 458

REYNOLDS, S. H.
The Photo-Electric Cell as a Smoke Detector .....XXIII: Mar., 135

RHODES, E. F.
Power-Factor Correction in Steel Mills .....XXIII: June, 287

RICHARDS, H. N.
Trolley Wire for Mine Service..... .....XXV: May, 237

RICHTER, H.
Evolution of Alternating-Current Secondary Networks.....XXII: July, 820
Alternating-Current Networks (E)... .....XXV: Feb., 57

RICKETTS, EDWIN B.
Power Plant Development as Seen by the Prime Movers Committee (E) .....XXV: June, 261

RIGSBY, J. P.
Building Large Steam Turbine Spindles .....XXIV: Dec., 591

RIKER, CHAS. R.
Design Research (E)....XXI: Mar., 87
Power Service for the Steel Industry in the Pittsburgh District..... ..... XXI: Sept., 442
Revamping Transmission Systems (E) .....XXI: Nov., 497
Lap Windings with Unequal Coil Groups .....XXII: Jan., 25
Influence of Radio on Power Development (E) .....XXII: Feb., 51
Magnetic Analysis (E) ..XXII: Mar., 101
A Perspective View (E)..XXII: Apr., 152
More Installation Experiences (E).. ..... XXII: May, 201
Alternating-Current Distribution Networks (E) .....XXII: July, 313
Underground Cables (E) XXII: Aug., 865
The Steel Mill as a Motor Proving Ground (E) .....XXII: Sept., 412
Let Your Light So Shine (E) ..... ..... XXII: Nov., 519
Then and Now (E) ....XXIII: Jan., 1
The Topical Index (E) .XXIII: Jan., 3
The Most Costly Fuel is Cheapest (E) .....XXIII: Nov., 547
What Price a Prize? (E) XXIII: Nov., 547
Our Mechanical Slaves (E)..... .....XXIV: Feb., 53
A Personal Inventory (E)..... .....XXIV: Mar., 95
The Control's the Thing (E)..... .....XXIV: May, 193
An Instrument for Progress (E).... .....XXIV: Aug., 363
$75 000 000 to Save Twenty Minutes (E) .....XXIV: Nov., 532
It's the Limit (E).....XXV: Feb., 58
Short-Hand Mathematics (E)..... .....XXV: Mar., 117
A Demon Enslaved (E)..XXV: May, 209
The Mathematics of the Amoeba (E) .....XXV: Aug., 373
Balancing in the Field (E)..... .....XXV: Dec., 574

RILEY, L. G.
Railway Control Protective Systems.. .....XXIV: Jan., 33
Fundamentals of Blow-Out Structures .....XXV: Oct., 485; Nov., 553

ROBINSON, P. H.
Practical Considerations Affecting Quick-Response Excitation for Salient Pole Machines ...XXV: Feb., 65

RODMAN, C. J.
Switch Oil Requirements and Characteristics .....XXII: May, 216

ROE, A. C.
Methods of Lapping Tape XXV: July, 365
Armature Coils Used to Maintain Railway Motors ..... .....XXV: Oct., 489; Nov., 549
Stripping Impregnated Motor Windings .....XXV: Oct., 520
Cleaning Commutator Bars..... .....XXV: Nov., 568

ROLPH, T. W.
Directional Control of Light for Street Illumination ..XXIV: Feb., 69

ROLLOW, J. G.
Seal Beach Power Station—Los Angeles Gas & Electric Corporation, Los Angeles, California....XXII: June, 281

ROSENBACH, SAMUEL
The 4000 Volt Distribution System of the Duquesne Light Company .... .....XXII: June, 289

ROSS, M. D.
The Multiple Path Radial Ventilation of Large Turbo-Alternators..... ..... XXI: Dec., 540
A New Type of Turbogenerator Rotor Insulation .....XXV: Feb., 63

ROSSELL, W. T.
Opportunity in the Street Railway Industry (E) .....XXV: Oct., 475

RUGG, W. S.
Super-Power from the Human Standpoint (E) .....XXI: Jan., 1
The Field of the EngineerXXIII: Dec., 589
Something New in Standards (E).... .....XXV: June, 265

RUSSELL, CHARLES J.
Power-Factor Correction in Philadelphia .....XXI: May, 201

RYAN, JAS. J.
The Field Balancing of Rotors..... .....XXV: Dec., 596

RYLANDER, J. L.
Testing Insulation with High Frequency .....XXV: Jan., 10

SAMMIS, W. H.
Industrial Electric Heating Accomplishments (E) .....XXIV: June, 246

SANDERS, H. M.
Low Voltage Testing Outfits .....XXIII: Dec. 604

SANDFIELD, M.
Soldering Joints in Electrical Windings—Pouring vs. Soldering Iron.. ..... XXI: Nov., 534

SANDS, H. T.
Public Relations (E) ....XXI: May, 191
The Wider Scope of Our Service Obligation (E) .....XXII: June, 245
American Initiative and American Cooperation (E) .....XXIV: June, 236
Strive for Higher Standards of Public Service (E) .....XXV: June, 255

SANTINI, D.
Electric Elevator Practice—IX—Testing of Elevator Equipments .....XXIII: Nov., 572

SARVAS, OTTO
Electric Truck Battery Charging Equipment .....XXI: Apr., 186

SAWIN, G. A.
Good Street Lighting Pays (E)..... .....XXIV: Feb., 53

SAWYER, W H.
Service Versus Rate of Fare (E) ... ..... XXII: Oct., 468
Now, as to the Bus (E).XXIII: Oct., 491
Sound Business Economics vs. Expediency in Urban Transportation (E) .....XXIV: Oct., 473

SCARLOTT, C. A.
Induction Motor Starting Torque .....XXIII: Nov., 582
A Mine Locomotive for Thin Seams .....XXIV: Oct., 493
Electrical Control Insures Safe Operation of Large Bascule Bridge..... .....XXIV: Oct., 516
Electric Snow Melters Protect Switch Tracks .....XXIV: Nov., 562

SCHAEFFER, GEO. H.
Status of Small Size Arc Furnace for Melting Steel (E) ....XXI: Sept., 401
Electric Heat (E) .....XXII: Sept., 410
The Association of Iron and Steel Electrical Engineers (E) .....XXIII: June, 271
Standardization in the Steel Industry (E) .....XXIV: July, 310

SCHAELCHLIN, W.
Contact Resistance of Electric Switching Apparatus .....XXV: Aug., 386

SCHAIRER, O. S.
Relations of Inventions and Patents to Development .....XXI: Oct., 487

SCHMIDT, HENRY F.
Fluid Governors for Prime Movers:
I—Historical .....XXV: Apr., 168
II—Type Characteristics ..... .....XXV: May, 238
III and IV—Operating Mechanism... .....XXV: June, 303; July, 354
V—Governing Impellers .XXV: Aug., 406
VI—Remote Control ...XXV: Sept., 451

SCHMIDT, J. D.
New 40 000 Kilowatt Turbines for the Duquesne Light Company ..... .....XXV: Jan., 36


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SCHOELLKOPF, PAUL A.
Should Our Water Power Resources be Developed (E) ..... XXV: June, 262

SCHOENFELD, O. C.
Effect of Unbalanced Voltages on the Operation of Induction Motors ..... XXII: Jan., 30
Induction Motors as Autotransformers . . .....XXIV: Aug., 381

SCHRAMM, W. H.
Dead-Front, Steel-Panel Switchboards . . .....XXIII: May, 247

SCOTT, CHAS. F.
Twenty Years of Growth (E)..... XXI: Feb., 52
The Beginning of Superpower (E).. ..... XXI: May, 200
Steel Tower Transmission Lines (E) ..... XXII: Jan., 1

SCOTT, WIRT S.
Industrial Electric Heating..... ..... XXI: May, 229
Operating Costs and Industrial Electric Heating .....XXI: June, 288
Manufacturing by Electric Heat . . .....XXIII: Nov., 548

SEELEY, H. B.
Parallel Operation of Direct-Connected Auxiliary Generators XXI: Aug., 387

SHAND, E. B.
Mercury Arc Rectifier Characteristics . . .....XXIV: Oct., 486

SHANNAHAN, JOHN N.
A Word of Encouragement (E)..... ..... XXII: Oct., 461

SHAW, C. H.
Progress in Underground Distribution (E) . . .....XXIV: June, 249

SHEELY, R. R.
The Wound-Rotor Induction Motor—Its Performance and Operation at Reduced Speeds . ....XXV: July, 342

SHEPARD, F. H.
The Virginian Electrification (E)... .....XXI: June, 258

SHEPHERD, C. H.
Financing Street Lighting Systems.. . . .....XXIV: Feb., 67

SHIRK, WM. B.
Advantages of Adjustable-Speed Drives for Rolling Mills ..... .....XXII: Sept., 414
Steel-Mill Type Safety-Switches..... . . .....XXIV: July, 327

SHOEMAKER, R. S.
The Association of Iron & Steel Electrical Engineers .....XXI: Sept., 399
The Convention (E) ....XXII: Sept., 411

SHOUP, PAUL
The Economic Utility of the Self-propelled Bus in Conjunction with Electric Railway Service in California .....XXII: Oct., 478
Why Greater Transportation Taxes for the Many than for the Few? (E) .....XXIII: Oct., 493
What the Public Should Know about Electric Railways (E)..... .....XXIV: Oct., 475
Are We Too Near the Trees to See the Forest? (E) .....XXV: Oct., 471

SILBERSTEIN, JAMES
The Development of a New, High-Temperature Solder ...XXV: Nov., 543

SIMMON, KARL A.
Electric Drive Possibilities for Railless Self-Propelled Vehicles..... ..... XXII: Oct., 481

SIMONS, DONALD M.
Sheath Losses in Cables (E)..... ..... XXI: Feb., 51
Measuring Dielectric Loss in Cables (E) .....XXII: Feb., 51
Calculation of the Electrical Problems of Transmission by Underground Cables .....XXII: Aug., 366
Calculation of Current-Carrying Capacity of Type H Cable XXIII :Feb., 59
Inductive Losses in Three-Conductor Type H Cables . ....XXIV: Mar., 115

SKILLEN, J. P.
Zero Mutual Inductance Positions of Coils with Parallel Axes..... ..... XXII: Dec., 583

SKINNER, C. E.
The First World Power Conference (E) .....XXI: Sept., 402
New A. I. E. E. Standards (E).... ..... XXII Sept., 412
International Electrical Standardization (E) .....XXIV: Dec., 577

SKINNER, C. R.
The Relation of the Central Station to the Electric Truck Industry..... ..... XXI: Apr., 133

SLATER, E. A.
1500 Horse-Power Kraemer Speed Set for the Columbia Steel Corporation, Pittsburgh, Calif ..... .....XXIV: July, 322

SLOAN, M. S.
Facts to Drive out Misconceptions (E) ..... XXII: Apr., 149
The Privilege of Public Service (E) .....XXIII: Mar., 93
Let's Make America Thrill with Pride of the Electrical Industry (E).... .....XXIV: June, 237
The Electrification of America (E)... .....XXV: June, 257

SMEDE, L.
High-Voltage Mercury-Arc Rectifiers .....XXV: Aug., 403
Automatic Vacuum Gauges ..... .....XXV: Sept., 437

SMITH, B. H.
A Universal Meter for Electric Power .....XXI: Mar., 112
The Transmission of Meter Readings by the Impulse Method XXI; May, 219
Remote Metering by the Impulse and Condenser Method .....XXI: Aug., 855

SMITH, H. B.
Build Up the Electric Truck Industry (E) .....XXI: Apr., 131

SMITH, HOMER K.
The Virginian Railway Electrification ..... XXI: June, 275

SMITH, H. W.
The Removal of Limitations (E) .....XXIII: July, 338

SMITH, I. C.
Some Problems of Parallel Operation of Direct-Current Generators .....XXIII: Aug., 407

SMITH, J. H.
The Steam-Jet Condensing-Type Vacuum Pump .....XXII: Jan., 17

SMITH, L. L.
The Design and Manufacture of Blading for Steam Turbines at the South Philadelphia Works ...XXII: May, 202

SMITH, M. W.
A 35 000 Kw Synchronous Frequency Changer Set .....XXI: July, 343

SMITH, T. F.
Financing Public Utilities ..... .....XXIV: Dec., 596

SNIFFIN, E. H.
Ralph E. Gilman—An Appreciation (E) .....XXI: Jan., 4
Steam Turbine Design (E) XXI: Nov., 497
The Engineer Salesman (E) ..... .....XXIV: Sept., 415

SODERBERG, C. R.
The Vibration Problem in Engineering.....XXI: Jan., 89; Feb., 53; Mar., 89; Apr., 160; June, 295 .....July, 330; Dec., 579
Vibration Absorbers for Large Single-Phase Machines .....XXI: Aug., 883
Measurements of Technical Vibration Phenomena .....XXIII: Feb., 71

SONTUM, W. C.
Changing a Transmission System to Operate at Double Voltage..... .....XXIV: June, 265

SOUTHMAYD, C. L.
Making the Small Turbine Safe..... .....XXV: Oct., 514

SPEER, JAS. W.
Modern Practice of Handling Coal in Bulk at Coal Piers.....XXI: June, 260

SPEIGHT, H.
Synchronous Motor Applications..... .....XXV: May, 219

SPOONER, T.
The Value of Commercial Magnetic Testing .....XXI: Aug., 874
The Properties and Testing of Magnetic Materials:
I—Characteristics of Magnetization and Permeability Curves ..... ..... XXII: Feb., 78
II—Normal Hysteresis and Eddy Currents .....XXII: Mar., 132
III—Range of Permeability and Core-Loss Values .....XXII: Apr., 180
IV—Range of Permeability and Core-Loss Values .....XXII: May, 230
V—Permanent Magnet Steels ..... ..... XXII: Aug., 394
VI—Hysteresis under Special Conditions .....XXII: Sept., 441
VII—Effect of Frequency on Permeability and Losses .....XXII: Oct., 508
VIII—Effects of Direction of Grain and Mechanical Stress on Magnetic Properties .....XXII: Nov., 554
IX—Effect of Heat Treatment..... ..... XXII: Dec., 610
X—Effect of Heat Treatment .....XXIII: Jan., 24
XI—Effect of Temperature . . .....XXIII: Feb., 79
XII—Alternating-Magnetizing Current and Mechanical and Thermal Properties of Electrical Sheet .....XXIII: Mar., 106
Magnetic Analysis .....XXII: Mar., 118
Audio-Frequency Transformer Characteristics . . .....XXIII: July, 367

STAHL, C. J.
Planning Ahead for Street Lighting.. . . .....XXIV: Feb., 63

STAHL, NICHOLAS
The Prime Movers Committee during 1923 and 1924 (E).....XXI: May, 189

STANDING, A. J.
Electrical Maintenance in the Steel Mill (E) .....XXIII: June, 272
The Operator's Relation to Safety in Steel Mills (E) .....XXIV: July, 308
Friendship in Engineering and Business (E) .....XXV: July, 319

STANLEY, JOHN J.
Welcome, A. E. R. A. (E)..... .....XXIII: Oct., 495

STEVENS, R. P.
Electric Railway Financing (E)..... ..... XXII: Oct., 464
Our Major Traction Problems (E) .....XXIII: Oct., 492
An Integral Part of the Community (E) .....XXIV: Oct., 474
What the A.E.R.A. Is Doing for the Industry (E) .....XXV: Oct., 469

STEWART, H. R.
Overvoltage on Transmission Lines During Generator Runaway ..... .....XXIV: Dec., 607

STICKNEY, F. S.
The Centrifugal Frequency Recorder .....XXV: Nov., 547

STINEMETZ, W. R.
Gas-Electric Cars and Diesel-Electric Locomotives (E) .....XXII: Oct., 470
What the Gas-Electric Car Means to the Railroads . .....XXIV: Oct., 494

STOKES, H. E.
Direct-Current Machines for Merchant Marine Drive .....XXI: Nov., 520
Reversing Mill Driving Equipment .....XXIII: June, 306
Structural Features of an 8 000 Hp Reversing Direct-Current Mill .... Motor . . .....XXV: July, 348

STOLTZ, G. E.
Wound-Rotor Induction Motors and Synchronous Motors for Rolling Mill Service .....XXII: Sept., 421
Increasing the Use of Electricity in Steel Mills (E) .....XXIII: June, 274
Building a Mill around a Motor (E) .....XXIV: Sept., 415
Cost Reductions by Labor-Saving Devices . . .....XXV: May, 217

STONE, E. C.
Standardization and Progress (E) .....XXIII: May, 208
Present Trends of Central Station Development (E) .....XXV: Jan., 1
The Engineering National Section (E) .....XXV: June, 260
The Public Utility Engineer (E)..... .....XXV: Nov., 527

STORRS, LUCIUS S.
Selling Transportation (E) .....XXIII: Oct., 493
Improved Relations Between the Public and the Railways (E)..... .....XXIV: Oct., 477
Local Transportation Conditions in the United States (E) ..... .....XXV: Oct., 473

STRASSER, JOHN
Stability of Alternating-Current Turbine Generators with Fluctuating Loads . . .....XXIII: Aug., 413

SULLIVAN, J. V.
Getting the Business (E)XXIV: Oct., 478

SUMNER, W. A.
Loading Transformers on a Temperature Basis .....XXII: Nov., 551
Modern Manufacture of Distribution Transformers . .....XXIV: Mar., 122

SUTTON, H. C.
The Work of the Overhead Systems Committee (E) .....XXIV: June, 246

SWOISH, W. R.
Supervisory Control ...XXIII: June, 311

SYKES, WILFRED
The Trend of Steel Mill Rehabilitation .....XXII: Sept., 418

SYLVESTER, J. W.
Work of the Underground Systems Committee (E) . .....XXV: June, 263

TADDIKEN, U. A.
Factors Which Influence the Performance of a Steam Surface Condenser . . .....XXV: Mar., 160

TANBERG, R.
Stresses in Bus Supports ..... .....XXIV: Oct., 517

Digitized by Google

TENNEY, H. W.
Photography of Arcs . . .XXIII: May, 249

TENNY, T. A.
The Use of Steel in Switchboard Design . . . . . .XXV: Dec., 613

TERVEN, L. A.
Radio Interference from Lines Not in Service . . . . . .XXIV: Jan., 13

THORNTON, JR., FRANK
Heater Cord Standards (E) . . . . . .XXV: June, 264

THORNTON, R. T.
Steel-Mill Motor Ventilation . . . . . .XXIII: June, 284

TRACY, J. H.
Storage Batteries in the Hands of the Individual User . . . . .XXIV: Mar., 128

TRIPP, GEN. GUY E.
Our "Far Eastern" Neighbors to the West (E) . . . . . .XXI: May, 194
National Electric Service XXII: June, 255

TRUMPLER, WM. E.
The Dynamic Balance of Small High-Speed Armatures . . . .XXII: Jan., 84

TUBBS, L. G.
Selection and Application of Induction Voltage Regulators . . .XXV: Nov., 529

TULEY, C. B.
Air Ejector Selection for Surface Condenser Installation (E) . . . . . .XXV: Dec., 572

TURNBULL, W. D.
Recent Developments in Permissible-Type Equipment . . . . .XXV: May, 231

UNDERHILL, CHAS. R.
Simplicity and Success (E) . . . . . .XXIII: Feb., 51

VALENTINE, C. E.
Automatic Railway Substations in Japan . . . . . .XXIII: Oct., 513

VAN SICKLE, R. C.
The Calculation of Current Values of Asymmetrical, Sinusoidal Waves. . . . . .XXIV: Sept., 450

VAUGHAN, V. G.
The Bimetallic Disc Type Thermostat . . . . . XXI: Nov., 582

VEINOTT, C. G.
The Transformer V Connection . . . . . .XXV: Feb., 110
A Method for Testing Transformers and Meters at Reduced Power-Factors Using Non-Reactive Loads. . . . . .XXV: Oct., 521

VICKERS, LESLIE
The Economic Position of the Street Railway . . . . . .XXIV: Oct., 500

WAGNER, C. F.
Impedance of a Rotating Synchronous Machine to a Negative Sequence Voltage . . . . . .XXIV: Mar., 117
Symmetrical Components:—
I—Resolution of Vectors Into Symmetrical Co-ordinates .XXV: Mar., 151
II—Resolution of Three Vector Products Into Products of Their Symmetrical Components . XXV: Apr., 194
III—Calculation of Unbalanced Faults . . . . . .XXV: June, 307
IV—Calculation of Faults on Systems with Lumped Constants . . . . . .XXV: July, 359

WALBRIDGE, J. B.
Recent Developments in Steam Turbine Cylinder Joint Fastenings. . . . . .XXV: Apr., 197

WALES, S. S.
The Interchange of Power Between Steel Mills and Central Stations (E) . . . . . XXII: Sept., 411
The Passing of the Reciprocating Engine (E) . . . . . .XXIII: June, 272
Central Station Power (E) . . . . . .XXIV: July, 307

WALLAU, H. L.
Relative Frequency of Voltage Surges Induced by Charged Clouds. . . . . .XXV: Aug., 374

WALZ, J. O.
Characteristics of Single-Phase Motors . . . . . .XXIII: Sept., 461

WARHUS, O. F.
The Gas-Electric Bus for Steam Railway Service (E) . . . .XXIII: Oct., 494

WEBER, C. A. M.
Winding and Connecting Small Single-Phase Motors . . . . . .XXI: Aug., 877

WENSLEY, R. J.
Automatic Substations for Edgar Thomson Works of the Carnegie Steel Company . . . . . .XXI: Sept., 409
Automatic Operation of Electrical Equipment (E) . . . . .XXIII: Apr., 149
The Development of the Televox. . . . . .XXIV: Dec., 601

WESTCOTT, D. E.
The Application of Remote Control to Modern Street Lighting . . . . . .XXIV: Feb., 56

WHEELER, F. S.
Recent Developments in Electrical Laboratory Equipment XXII: Nov., 544

WIGGINS, A. M.
Iron Core Reactors with Air-Gaps—An Approximate Method of Design . . . . . .XXIV: Jan., 20
Direct-Current Reactors XXIV: Nov., 563
Ring Type Current Transformers. . . . . .XXIV: Dec., 621
A New Portable Oil Testing Set. . . . . .XXV: June, 301

WILCOX, H. M.
High Power Direct-Current Tests . . . . . .XXIII: Oct., 524

WILEY, BRENT
Steel Mill Improvements (E) . . . . . XXI: Sept., 402
Reducing Steel Mill Operating Costs (E) . . . . . .XXIII: June, 275
Electrification of Industry Means Increased Profits (E) . . . . . .XXIV: July, 310
The Value of Electrification to the Steel Mill Industry . . . . . .XXV: July, 321

WILMETH, ROSCOE
Commercial Methods of Carbon Resistance Measurement . .XXI: July, 809

WILSON, G. P.
Automatic Substations in Steel Mills . . . . . XXII: Sept., 428
Care and Maintenance of Renewal Parts for Electrical Equipment. . . . . .XXIV: July, 333
The Electrification of No. 3 Rod Mill at the Worcester Works of American Steel & Wire Company. . . . . .XXV: July, 323

WILSON, R. L.
Organization and Man Power (E). . . . . .XXV: Feb., 58

WIMMER, E. P.
Delta-Connected Transformers Loaded at Full and Half Voltage . . . . . XXII: Feb., 66

WISHON, A. EMORY
When Customers are Partners (E) . . . . . XXII: June, 250

WOHLGEMUTH, M. J.
Analysis of Oil Circuit Breaker Requirements for Large Steel Plants . . . . . XXI: Sept., 411
Steel Enclosed Switching Equipment for Steel Mill Service XXII: Sept., 417
Recent Developments in Switching Equipments for Industrial Plant Electrification . . . .XXIII: June, 298

WOLFERT, E. R.
The Development of the Feeder Voltage Regulator . . . . . .XXV: Sept., 441

WOLL, WILLARD M.
Current Carrying Capacity of Bare Cables . . . . . .XXIII: Nov., 557

WOOD, L. A. S.
The Appraisal of Street Lighting. . . . . .XXIV: Feb., 55
Hollowspun Concrete Poles . . . . . .XXIV: Dec., 603

WOODROW, H. R.
The Fundamental Plan in the Electrical Design of the Hudson Avenue Generating Station of the Brooklyn Edison Company . . . .XXII: Apr., 158
Fourth Unit Extension for the Hudson Avenue Generating Station of the Brooklyn Edison Company. . . . . .XXII: July, 855
Good Engineering in Power Generation and Distribution (E) . . . . . .XXIV: June, 245

WOODS, G. M.
The Indianapolis & Cincinnati Traction Company. . . . . .XXI: Oct., 464
Tendencies in the Design of Modern Cars . . . . . .XXIV: Oct., 483
Developments in Street Car Drives (E) . . . . . .XXV: Oct., 476

WOODWARD, W. R.
The Application of Decrement Factors in Short-Circuit Studies XXI: May, 213
A High-Power Laboratory for Testing Oil Circuit Breakers and Other Apparatus . . . . . .XXIII: Mar., 102
A Laboratory for Testing the Interrupting Capacities of Direct-Current Circuit Breakers . . . . . .XXIV: Oct., 502
An Extension of the High-Power Testing Laboratory . . .XXV: Mar., 139

WRIGHT, R. H.
Electrification of Rolling Mills in the Structural Department, Homestead Works, Carnegie Steel Co. . . . . .XXIV: Sept., 419

WURTS, T. C.
The New Norfolk & Western Locomotives . . . . . XXI: June, 280

WYMAN, M. B.
Motors and Control for Pulverized Fuel Plants . . . . . .XXIII: May, 236

YARDLEY, J. L. McK.
Electric Power for Chemical Plants . . . . . .XXIII: Mar., 113

ZAHOUR, ROBERT L.
Cleaning and Maintenance—A Remedy for Lighting Maladies XXIII: May, 259

ZEUTHEN, ERNST
Power Station Control Boards— Advances in Design for the Toronto Power Station and Boardman Substation of the Ohio River Edison Company . . . . . .XXIII: Jan., 4


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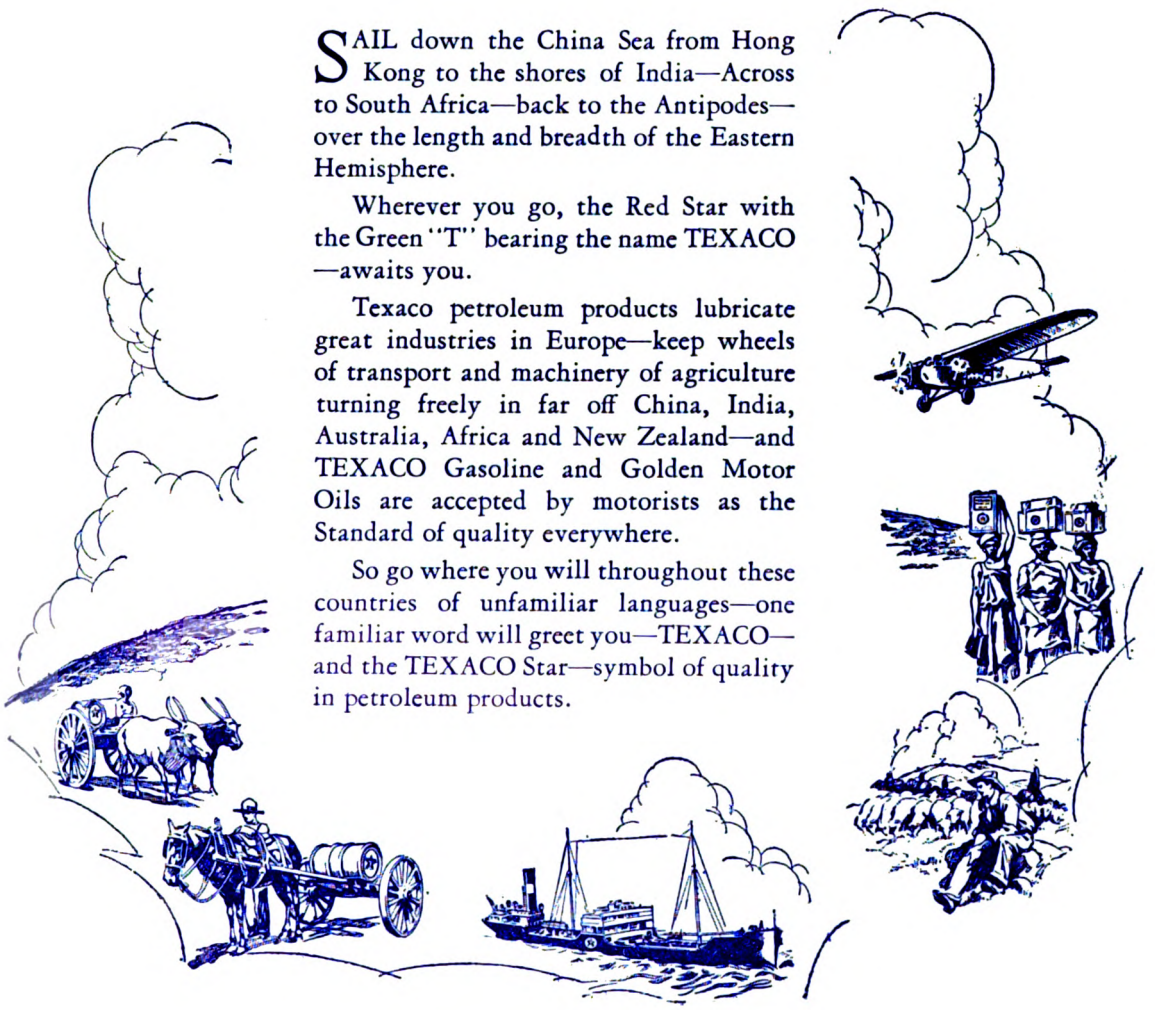

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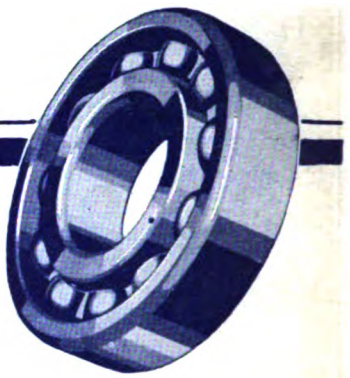

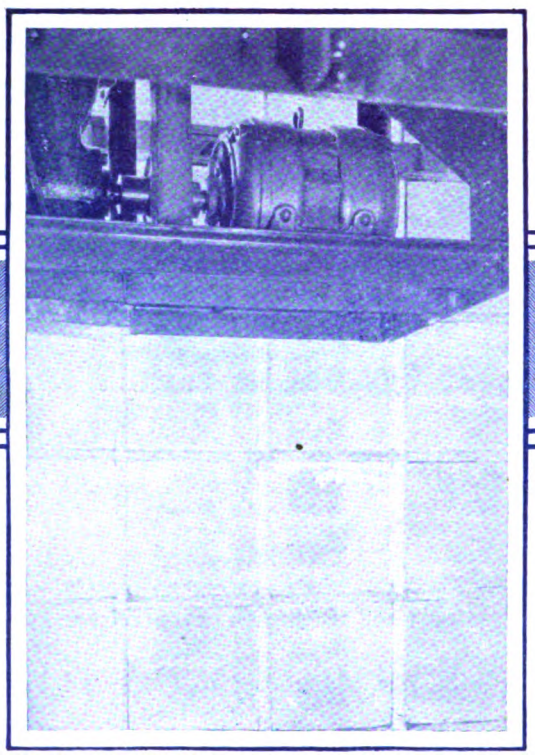

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